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CHANGING FLOOD FREQUENCY IN SCOTLAND: IMPLICATIONS FOR CHANNEL GEOMORPHOLOGY, ECOLOGY AND MANAGEMENT

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CHANGING FLOOD FREQUENCY IN SCOTLAND: IMPLICATIONS FOR CHANNEL GEOMORPHOLOGY, ECOLOGY AND MANAGEMENT

By

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“Success in life comes when you simply refuse to give up, with goals so strong that obstacles, failure, and loss only act as motivation”

Anonymous

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Author's Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Sub-Committee.

Work submitted for this research degree at the Plymouth University has not formed part of any other degree either at Plymouth University or at another establishment.

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Abstract

The effect of climate on the fluvial system has long been investigated due the significant impact it can have on a river's hydrological regime and fluvial processes. In recent years this interest has increased as global changes in climate are expected to bring more frequent high magnitude flood events globally and to North West Europe in particular. Despite the knowledge that the frequency and magnitude of floods is to increase, less is known about the geomorphological implications of this for river channels and where channel instability is likely to occur at both the river network and national scale. This is certainly the case in Scotland where increased flooding is expected and large floods have been abundant over the last two decades. To manage Scottish river catchments effectively in the future, in terms of hazard mitigation and nature conservation, river managers need to be able to predict not only how climate will impact flood magnitude and frequency in Scotland but the effect these changes will have on the internal dynamics of river channels in terms of erosion, sediment transport and deposition, and morphological dynamics. Such knowledge will ensure adequate measures are implemented to reduce fluvial risks to humans and to maintain and preserve valuable river habitats and linked species.

In this thesis, several novel methods incorporating field, laboratory and GIS-based analysis, have been investigated as a means of predicting how climate change will affect channel stability in Scottish rivers and the implications of this for river management and river ecology. This includes (i) analysing the potential change in the frequency of geomorphologically-active flood flows with climate change; (ii) the use of stream power thresholds to predict changes in channel stability on a national scale with climate change; and (iii) using a Digital River Network developed using geospatial data to predict changes in the rate of bedload transfer and channel stability with climate change. Studies were undertaken on 13 different rivers across Scotland from north to south and east to west.

As a case study of ecological implications, the thesis also examines how changes in habitat and stability of freshwater pearl mussels (*Margaritifera margaritifera*) may be altered by increased flooding. Predictions of the frequency of geomorphic activity, channel stability, rate of bedload transfer, and the stability of freshwater pearl mussel habitat with climate change are discussed along with the methods used to obtain these outcomes.

The results all suggest an increase in the frequency and rate at which bedload is transferred through the river system and an increased frequency of flood flows resulting in greater channel instability. Morphological responses vary spatially with some river reaches experiencing greater increased erosion and transport potential than others. Climate change effects on the freshwater pearl mussel are: increased occasions of disturbance and transport downstream and the importance of specific populations in more stable environments for ensuring population recovery post flooding is highlighted. It is hoped that the methodologies developed for predicting changes in channel stability with climate change will provide useful screening tools to regulatory agencies which can be developed further to assist management decisions in the future which aim to reduce fluvial hazards and maintain good quality river environments for the species that inhabit it. The approaches used in this study allow for the identification of areas at high risk of morphological and ecological change, and the pro-active planning and management of sediment-related river management issues and nature conservation.

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List of Acronyms and Abbreviations

AGE	Annual Geomorphic Energy
CAESAR	Cellular Automaton Evolutionary Slope and River
CAR	Controlled Activities Regulations
CBS	Catchment Baseline Survey
CEH	Centre of Ecology and Hydrology
CRESS	Centre for River EcoSystem Science
CUSUM	Cumulative Sum Control Chart
DRN	Digital River Network
DEM	Digital Elevation Model
D_b	Median grain size for the whole bed in meters
D_i	Grain size entrained by the flow in meters
D_{10}	Bedload grain size 10% of the bed is finer than
D_{50}	Median bedload grain size
D_{84}	Bedload grain size 84% of the bed is finer than.
EU	European Union
FA	Fluvial Audit
GIS	Geographical Information System
GLM	Generalised Linear Model
HEC-RAS	Hydrologic Engineering Centre - River Analysis System
IHACRES	Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation and Streamflow Data
IUCN	Internal Union for the Conservation of Nature
g	Acceleration due to gravity
LiDAR	Light Detection Ranging
Kg	Kilograms
m	Meters

mm	Millimetres
NAO	North Atlantic Oscillation
NAOI	North Atlantic Oscillation Index
NFM	Natural Flood Management
RHS	River Habitat Surveys
RMSE	Route Mean Squared Error
OS	Ordnance Survey
ρ	Specific Weight of Water
POT	Peaks Over Thresholds
Q	Discharge
Q1	Quartile 1
Q2	Quartile 2 (median)
Q3	Quartile 3
$Q_{MED}/(\omega_{med})$	Median annual flood value
1:2	Flood with a recurrence interval of every 2 years
1:5	Flood with a recurrence interval of every 5 years
1:10	Flood with a recurrence interval of every 10 years
1:30	Flood with a recurrence interval of every 30 years
1:50	Flood with a recurrence interval of every 50 years
1:100	Flood with a recurrence interval of every 100 years
RSPB	Royal Society for the Protection of Birds
REAS	River Energy Audit Scheme
Ω	Stream Power
ω	Specific Stream Power
ω_{ci}	Critical Stream Power
S	Longitudinal slope
s	Seconds
SACS	Special Area of Conservation

SCM	Site Condition Monitoring
SEPA	Scottish Environment Protection Agency
SIAM	Sediment Impact Assessment Model
SNH	Scottish Natural Heritage
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
ST:REAM	Stream Transport Reach Equilibrium Assessment Method
UK	United Kingdom
UKCP09	United Kingdom Climate Projections 2009
USA	United States of America
w	Width of the water surface in meters
WFD	Water Framework Directive
Y	Mean channel depth

CHAPTER 1

Introduction: Flooding, Channel Stability and Climate Change

1.1 FLOODING IN SCOTLAND

Flood events across the UK in 2016 have highlighted once again their devastating effects. These events not only cause the significant social and economic costs that are primarily reported about in the news but also have considerable geomorphic and ecological consequences for the river itself. In Scotland on average, damage to businesses, homes and agriculture due to flooding costs an estimated £720-£850 million annually (Scottish Government, 2013) as well as incoming considerable stress and anxiety to those directly affected. Meanwhile within the river environment itself, extreme floods provide the river with more power to erode and transfer sediment often resulting in significant changes in channel morphology in terms of its shape and geometry. During the 'Storm Frank' flooding in January (2016) the local residences of Deeside witnessed a change in river geometry first hand when the River Dee's channel width increased so drastically that a section of the A90, the main road connecting Ballater and Braemar, was washed away and Abergeldie Castle, which has resided on the banks of the River Dee for 466 years, very nearly crumbled into the river. These changes in channel morphology benefit river biota by creating new habitats and cleansing the river bed by removing unwanted silts and macrophyte (Resh et al., 1988, Bunn and Arthington, 2002). However, changes in channel morphology can negatively affect river biota by directly killing or displacing the species or significantly altering habitat structure, which can disturb breeding and encourage the invasion and spread of new species (Gordon et al., 1992; Bunn and Arthington, 2002). Declines in freshwater pearl mussel populations on the River Kerry following a 1:100 year flood provides a good example of this (Hastie et al., 2001). Around 50,000 (4-8% population) mussels were killed due to becoming stranded on banks, being crushed or damaged by mobile bedload or being washed out to sea, in addition to considerable scouring of previously favourable habitats (Hastie et al., 2001).

In recent years there has been a move towards natural flood management (NFM) in order to try and reduce the social and economic costs of flooding while at the same time improving the river environment for aquatic ecology (Forbes et al., 2015). NFM involves using more sustainable softer engineering practices aimed at holding flood waters in the upper catchment for longer and slowing down the speed at which flood water reaches the lower catchment which tend to have higher population densities. Methods currently used in natural flood management to mitigate against floods include afforestation, improved riparian vegetation, channel re-meandering and greater floodplain inundation. However, how these practices hold up within an environment with a changing climate is yet to be witnessed.

Future changes in climate and flow are likely to present a new challenge to river managers and those who live and work along the banks of rivers. Current predictions (Arnell and Reynard, 1996; Cameron, 2006; Wilby et al., 2008) suggest that the frequency and magnitude of floods will increase in the future and the occurrence of what we presently consider to be an extreme flood could become closer to the norm. This would increase not only the volume of water that the river is required to convey but also the volume of sediment, as more sediment is likely to be supplied to the channel from the surrounding catchment. In the UK, it is generally proposed that river channels are on average adjusted to convey a 1:2 year flood (although this has been shown to vary between rivers (Harvey, 1969)) and thus flows greater than this will cause some gross adjustment in channel morphology often through erosion of the river bed and banks (Pickup and Rieger, 1979;

Andrews, 1980; Carling, 1988; Crowder and Knapp, 2005). As the magnitude of a 1:2 year flood, along with flows on either side of this value, is predicted to increase (Werritty et al., 2002) many river channels may adjust their morphology to accommodate this alteration in the hydrological and sediment regime to allow it to convey the larger volumes of water and sediment now associated with a greater flood return interval.

Previous studies which have investigated longer term evidence of river channel responses to climate change have shown changes in channel morphology are linked to major hydroclimatic trends which occur in Britain and northwest Europe (McEwen, 1989; Macklin et al., 1992; Rumsby and Macklin, 1994; Merrett and Macklin, 1999). Rumsby and Macklin (1994) found that changes in channel incision and stability coincided with changes in flood frequency which were associated with different atmospheric circulation patterns. Periods of channel incision occurred under meridional circulation patterns bringing a higher frequency of large floods (>20year return interval), whereas zonal circulation weather systems increased the frequency of moderate floods (5-20 year return interval) which enhanced lateral reworking and sediment transfer in upland channel reaches and channel narrowing in lowland channel reaches (Rumsby and Macklin, 1994).

The response of river channels and individual channel reaches to changes in the hydrological and sediment regime of the river will vary depending on their sensitivity to change and their proximity to a geomorphic threshold (Brunsden and Thornes, 1979; Werritty and Leys, 2001). An improved ability to predict which reaches within a river channel will be the most sensitive to a change in morphology or most likely to become unstable due to crossing a geomorphic threshold would provide river managers and policy makers with a better understanding of how and where these changes in the hydrological regime will have the greatest impact on morphology and ecology (Landres et al., 1999; Arthington et al., 2006). Currently, however little work has been undertaken investigating if the predicted increase in the frequency and magnitude of flooding in the future will i) cause Scottish river channels to become unstable and adjust their morphology to convey larger volumes of sediment and water and ii) where within a catchment or across Scotland these changes in channel morphology will occur. The ability to do this is important for a number of reasons, namely to enable river managers to reduce flood hazards, protect river ecology, implement management practices which are sustainable in a changing climate, and for European Union (EU) member states to ensure that requirements under the Water Framework Directive and Habitat and Species Directive will still be achieved in a changing environment.

1.2 MORPHOLOGICAL ADJUSTMENT

The potential changes in channel morphology caused by climate change mean fluvial geomorphologists have an important role to play in the future management of river channels to ensure channel adjustments due to climate change are accounted for and to ensure river management strategies implemented are sustainable (Forbes et al., 2015). Fluvial geomorphologists aim to find out the cause for sediment related issues and potential channel stability caused by different river activities (Sear and Newson, 2010). This is often done through interdisciplinary science and by taking a holistic view to ensure the interactions across the whole catchment are considered (Sear and Newson, 2010). This ability to take an interdisciplinary approach is a valuable fundamental concept and the theme of eco-hydromorphology has developed within river science, where the importance of the interplay and feedbacks in a river's hydrological and sediment regimes on river ecology is recognised (Vaughan et al., 2009). The geomorphology of river channels links to river ecology as it is responsible for the physical habitat characteristics of the channel which are in turn a result of the channels ability to erode, transport and deposit sediment, which is controlled by the channel's hydrological regime. To allow a fluvial geomorphologist to predict how changing land use, climate and river management practices may affect river ecology or create fluvial hazards such as flooding they need to be able to understand how changes in hydrology and sediment supply affect channel morphology. The River Styles Framework developed by Brierley and Fryirs (2005) is one river management approach which recognises and encompasses this link between geomorphology and ecology, in order, to predict a river channel's response to natural or human induced disturbance events. The River Styles Framework outlines a series of steps and tools which can be deployed to interrupt and understand the character, behaviour, condition and recovery potential of a river reach to provide a solid foundation for making management decisions (Brierley and Fryirs, 2000; 2002; Brierley et la., 2011). By taking this approach, a river management strategy can be developed that works with the natural processes within a channel and, in doing so, ensures that the diversity and behaviour of the aquatic ecosystem is maintained (Brierley and Fryirs, 2000). This approach has been built on further by Thomson et al., 2001 whereby the River Styles Framework was extended to include a habitat assessment procedure to link hydraulic and geomorphology, further highlighting the increased importance of linking geomorphology and ecology when making and predicting the outcomes of management decisions.

More traditional approaches to predicting changes in channel morphology are based on the classic work of Leopold and Maddock (1953) looking at 'hydraulic channel geometry'. This approach is based on the concept of 'regime theory' where a set of empirical equations and power law relations can be used to provide the width, depth and slope using input data on channel discharge, velocity and grain size (Knighton, 1998). Although originally developed for canals, theses equations have been developed to make them applicable to natural channels. More recently with advances in computing power, 1D and 2D and cellular automated models have been developed to predict channel change not only in the future but also how channels have adjusted and shifted their morphology over time scales of up to 10,000 years (Coulthard et al., 2000, 2005). These models, unlike the application of 'regime theory' or 'hydraulic geometry', attempt to take into account the complex interactions and feedbacks that occur within the fluvial system between channel shape, flow and sediment transport (Richards and Lane, 2008). One and two-dimensional models use a series of equations to route water and in some simulations sediment through a reach or to look at the differences between sediment entering and leaving channel reaches along a channel (Green, 2006; Thorne et al., 2010). Due to the computing power and data requirements needed to run such models they are often only applied to small sections of channel, for example a few 100 metres either side of a section of channel where bridge or culvert are to be located. Cellular models, in contrast simplify some of the more complex sediment and hydraulic equations and use the basic rules of physics to route water and sediment through an entire river catchment. The reduction in computing power by doing this allows simulations of channel change over a large range of temporal and spatial scales. Coulthard et al., (2005), for example, showed using the cellular model CAESAR that significant differences in bedload transport have occurred over time in response to Holocene environmental changes such as climate and land use change. This provides geomorphologists with a new way of looking at channel change over longer time scales and aids in the prediction and management of future adjustments in channel form by knowing how river channels adjusted historically.

Longer term evidence for looking at the response of river channels to climate change can be achieved by using paleo-hydrological techniques (Weil et al., 2010). Paleo-hydrological techniques involve the use of historic geomorphic, sedimentological and ecological data or alluvial archives to understand channel change and predict future changes in channel morphology (Sear and Arnell, 2006). Macklin and Lewin (2003) for example, investigated the sensitivity of British rivers to channel change due to global environmental changes using 14C Holocene alluvial units. Using this technique, it was established that global changes in climate and localised changes in land cover were reflected in the behaviour of the river system (Macklin and Lewin, 2003). Other techniques include the use of lichenometry, whereby lichen-dated flood deposits are evaluated to assess changing flood risk over temporal scales of up to 250 years (Macklin and Rumsby, 2007). The results show that there has been an increasing and decreasing occurrence in the magnitude and frequency of extreme flood events in the UK over the last 300 years and that the occurrence of extreme upland flooding in UK over the last 200-300 years is has been associated with a negative North Atlantic Oscillation Index

(Macklin and Rumsby, 2007). Furthermore, Macklin and Rumsby, (2007) showed that river-bed levels have correlated with rising temperatures over the last 100 years, highlighting further the usefulness of palaeohydrological techniques in understanding the response of river's changing climatic conditions. Further techniques for looking at longer term evidence for channel change include the use of historic maps and aerial photographs to look for changes in channel geometry and planform (Petts, 1989; Downward et al., 1994). McEwen (1994) successfully used historical maps and aerial photographs along with a Bausch and Lomb Zoom Transferoscope to map the channel planform of the River Coe at different time periods and a Tektronic digitiser to investigate planform adjustment on the River Coe in the Scottish Highlands since 1850. The use of palaeohydrological techniques have now also been suggested as having a key role to play in future river management by using evidence of what has occurred in the past as an indicator of what may occur in the future (Sear and Arnell, 2006).

Palaeohydrological techniques and many 1D and 2D models require considerable field surveying which is often expensive and time consuming. This can include a full Fluvial Audit or Catchment Baseline Study (Thorne et al., 2010) or cross-sectional surveys and an analysis of the channel bed. Recent advances and improved availability of spatial data have however opened the door to a different sort of quantitative modelling which builds on qualitative field assessments but without being data heavy and time intensive like many sediment routing models. Spatial data can provide river managers with a reliable estimate of channel width, channel slope, various flood discharges and channel sinuosity. For this reason, many current models use stream power as a means of predicting areas of channel instability and whether any change in channel morphology will occur through erosion or deposition. Stream power provides an estimate of the river ability to transfer sediment and does not require a depth or velocity value making it easy to calculate using spatial data. Predicting channel change using stream power became increasingly popular in the 1980's when Andrew Brookes (1987b) showed that adjustments in channel morphology by managed channels in England and Wales and Denmark tended to occur within set specific stream power band. Channels with a stream power of less than 10 Watts s^{-1} would adjust through deposition, above 35 Watts s^{-1} adjustment occurred through erosion and above 100 Watts s^{-1} channel shifting would occur (Brookes, 1987b). More recently the change in stream power between river reaches has been used to predict most dominant geomorphic process occurring (erosion, transport, deposition) within a reaches across an entire catchment (Vocal Ferencevic and Ashmore, 2012; Parker et al., 2015). These models provide a simple, physically-based and objective tool which is easy to use and develop with less time, data and expertise requirements.

However, as yet work using spatial data to predict how channel stability will change at different flood frequencies and also how changes in climate may influence this is more limited i.e. at what flood magnitude and frequency does a reach potentially start to adjust it morphology. Furthermore, many models developed do not tend to consider how the geomorphic processes occurring within a river affect river ecology, particularly benthic species which rely on having a stable river to maintain healthy populations. At a time when the importance of looking at the linkage between ecology, hydrology and geomorphology to ensure legislative objectives are achieved has been highlighted as essential, the ability of river mangers to screen a river catchment not only for potential channel instability but also at what flow different aquatic species become vulnerable and how this varies across the catchment could prove a useful tool.

1.3 RATIONALE, AIMS AND OBJECTIVES

1.3.1 Rationale

Although it is currently well documented that climate change is likely to increase the frequency and magnitude of flood flows in many parts or perhaps all of the UK, less work has focused on how this will affect channel stability, river ecology, locations within a catchment most vulnerable to change and a method to predict this that does not require complex knowledge of models and geomorphic processes. A change in the frequency of high flow events could potentially alter the stability and morphology of river channels leading to an increase in fluvial hazards and altering of the ecological processes and river reach health. Hey (1982, 1997) outlined nine ways in which a river channel can adjust it morphology known as a channel's degrees of freedom. These include changes in planform (sinuosity), cross-section adjustments (width and depth), slope and bedload load grain size. Therefore, any potential changes in channel stability and morphology need to be taken into account and incorporated into future river management schemes to ensure the effective implementation of river restoration projects, flood mitigation works and species management. A knowledge of how river channels will respond to an increase in the frequency of high flow events is critical in ensuring rivers maintain a good ecological status in terms of the EU Water Framework Directive and also in terms of site condition monitoring with respect to the EU Habitats and Species Directive.

1.3.2 Project Development

The development of this thesis has revolved around the use of the Scottish Environmental Protection Agency's (SEPA) Digital River Network and their ability to predict changes is channel stability at the national scale. Using this approach would allow SEPA to understand the advantages and limitations of using the Digital River Network as a means of looking national scale changes in channel stability and bedload transfer with different flood return intervals and under climate change. The data used to develop the methodologies used in this thesis to investigate ways of predicting channel change with climate change has been largely influenced by the data available from SEPA and Scottish National Heritage. This included the selection of study sites and the range of flood return intervals over which changes in bedload transport with climate change were investigated.

An evaluation of the use of the stream power thresholds devised by Andrew Brookes (1987a, b) for managed channels was reviewed as a means for assessing channel stability within Scottish rivers because these thresholds are the ones most commonly used by SEPA when making management decisions.

The decision to use the freshwater pearl mussel, as a case study, to investigate the wider application of the Digital River Network in relation to ecology was largely influenced by the Scottish National Heritage (SNH). The freshwater pearl mussel is a protected species monitored by SNH. It faces an uncertain future due to the potential threat of increased bed disturbance from a higher frequency of high flow events as a result potential changes in climate.

1.3.3 Aim

The aim of this thesis is to investigate how spatial data can be used to look at how flood frequencies and magnitudes in the past and in to the future under a climate change scenario will potentially affect channel geomorphology, ecology and management at catchment scales and conceivably the national scale.

1.3.4 Objectives

Objective 1: examine long-term flow records to look at the frequency of geomorphologically significant high flows on six geographically distinct Scottish rivers in the past and to predict potential future changes with climate change

- Enhance our knowledge as to whether there is increasing evidence to suggest Scottish rivers have under gone periods which have been flood rich and flood poor in the past.
- Establish whether any current trends found are regionally specific or apply to Scotland as a whole.
- Predict how future changes in climate will affect the frequency and magnitude of flood-induced geomorphic events.
- Consider how any changes in the frequency of flood-induced geomorphic events could affect future management decisions.

Objective 2: investigate the use of stream power as a proxy for channel change induced by flood scenarios and whether it can be used as a pre-screening tool by river managers to highlight potential areas of channel instability on a national scale

- Investigate how applicable the stream power thresholds for channel adjustment by deposition and erosion suggested initially by Brookes (1988) for managed channels in England and Wales are to the upland river catchments of Scotland
- In the event of Andrew Brookes's (1987a, b) stream power thresholds are not appropriate for Scottish river systems suggest alternative values or approach
- Investigate how climate change induced flood scenarios changes the dominate channel sediment transport process type during a 1:2 year flood

- Identify any regional difference (east, north and west Scotland) in the number of reaches which change channel process type with the predicted influence of climate change.

Objective 3: use and develop the Scottish Environmental Protection Agency's Digital River Network (DRN) to explore changes in channel stability and rate of bedload transfer at different flood frequencies and with climate change induced flood scenarios

- Develop a catchment-scale bedload transport model
- Develop a method to extract a channel depth value for each 50m DRN point to allow the rate of bedload transport to be calculated
- Use scientific literature and field data to assign a geomorphologically relevant particle grain size to each channel typology used within the DRN
- Assess the change in the rate of bedload transport with changing flood frequency climate change induced flood scenarios
- Assess the change in the rate of bedload transport between different channel typologies
- Assess the change in channel instability with changing flood frequency and climate change induced flood scenarios
- Carry out field survey work to aid in the validation of model outputs.

Objective 4: Assess the importance of habitat structure on allowing aquatic species to avoid entrainment with specific reference to the freshwater pearl mussel

- Develop a flume study to investigate entrainment velocities of freshwater pearl mussels within different habitat structures
- Assess the effectiveness of entrainment avoidance mechanism (burial, alignment, sheltering) used by mussels to avoid entrainment

Objective 5: look at the potential affect that changing in flood frequency and climate change could have on river ecology which reference to the critically endangered Freshwater Pearl Mussel

- Use the Scottish Environmental Protection Agency's Digital River Network (DRN) to explore which mussel populations in the River Dee are most vulnerable to changing flood frequency magnitude with climate change
- Explore the usefulness of using the DRN to assess the vulnerability of freshwater pearl mussels to extreme flood events and climate change

1.4 THESIS STRUCTURE

1.4.1 Thesis Synopsis

This thesis is composed of seven chapters with each chapter building on the findings of the previous chapter (Figure 1.1). Chapter 2 aims to investigate how an increase in winter rainfall will influence the occurrence of geomorphologically relevant flood events. The results from Chapter 2 show that the frequency of geomorphologically relevant winter floods will potentially increase under climate change. Chapter 3 evaluates the use of stream power thresholds as a means of predicting the river reaches most sensitive to a change in the frequency and magnitude of geomorphic flood events with climate change at the national scale, as was predicted to occur in Chapter 2 of this thesis. Chapter 3 concludes that the addition of a bedload element when looking at future changes in channel stability may more accurately predict which river reaches will be the most sensitive to future changes in channel stability. Chapter 4 adds a bedload element by using a bedload transport equation to investigate changes in the rate of bedload transport within river reaches to assess channel instability at various flood frequency magnitudes historically and under a climate change scenario. Chapter 5 highlights the importance of understanding future changes in channel bed stability for benthic ecology. This was achieved by looking at the importance of bed stability in preventing freshwater pearl mussels from being entrained downstream. In Chapter 6 the bedload transport model developed in Chapter 4 is combined with the findings in Chapter 5 which demonstrated the importance of bed stability for freshwater pearl mussels, to highlight at what flood frequency magnitude freshwater pearl mussel populations are most vulnerable to entrainment downstream historically and under a climate change scenario. As each chapter builds on the findings of the previous one it aids in contributing to a fuller

understanding of the potential impact of future climate change on flood frequency,

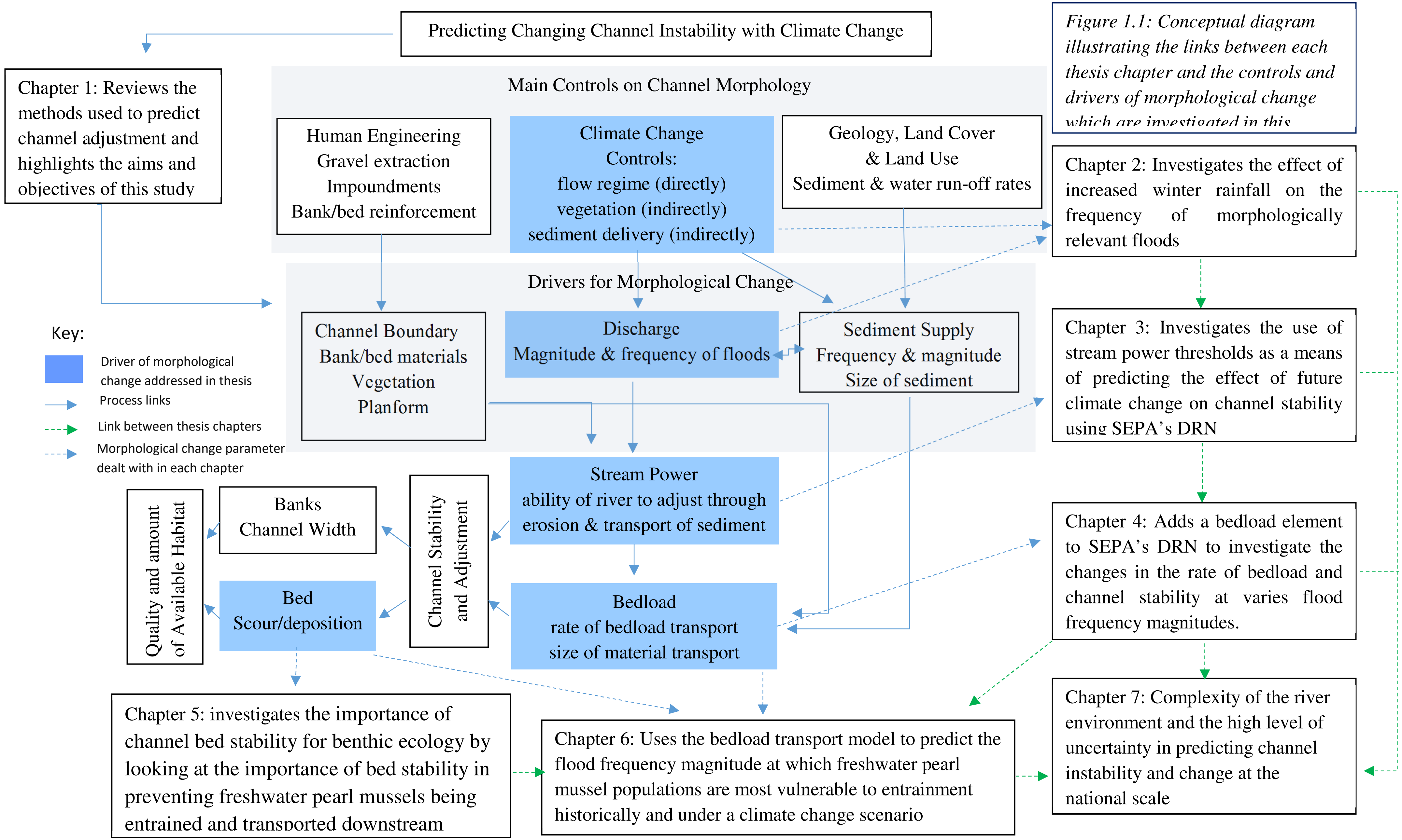


Figure 1.1: Conceptual diagram illustrating the links between each thesis chapter and the controls and drivers of morphological change which are investigated in this

channel stability, riverine ecology and river management to answer the aims and objectives of this thesis, which are addressed in Chapter 7.

1.4.2 Detailed Chapter Synopses

Chapter 1 provides an overview of the methods used to predict channel adjustment and highlights the aims and objectives of this study.

Chapter 2 looks at flow records which are greater than 50 years in length for six rivers across Scotland to investigate whether there is evidence to suggest Scottish catchments have undergone periods where the frequency of flooding has increased (‘flood-rich’) and periods where the frequency of flooding has decreased (‘flood-poor’). The change in the frequency of geomorphic flood events with climate change is also reviewed in addition to what the results means for the future management of Scottish rivers.

Chapter 3 investigates the suggestion that the stream power thresholds suggested by Andrew Brookes in 1988 for managed channel in England and Wales are applicable to Scottish river channels. Field data collected from six upland channels in Scotland were used to create threshold for channels which were erosion dominated and deposition dominated. The accuracy of these thresholds for predicting channel process type was then assessed and compared to the thresholds suggested by Brookes in 1988.

Chapter 4 investigates the use of Scottish Environmental Protection Agency’s Digital River Network to predict potential changes in channel stability and rate of bedload transport which changes flood frequency under pre-climate change and post-climate conditions. The River Dee in Aberdeenshire was used as a case study to assess the accuracy of the model’s outputs.

Chapter 5 outlines a flume study which was undertaken to establish the importance of habitat structure and the defence mechanism of burial, alignment and sheltering to allow the freshwater pearl mussel to avoid entrainment.

Chapter 6 outlines the use of Scottish Environmental Protection Agency's Digital River Network to predict at what flood frequency individual freshwater pearl mussel populations become unstable and how climate change may alter the frequency at which their habitats become unstable. The River Dee was used as a case study catchment to demonstrate the use of the Digital River Network for this application.

Chapter 7 is a concluding chapter which readdress the aims and objectives set out in chapter one of this thesis. This chapter reviews the finding for each of the five data chapters in order to answer the aims and objectives of this thesis. This chapter also makes some suggestions for further research in this area.

CHAPTER 2

Frequency of Flood Flows Associated with Geomorphic Activity within Scottish River Channels: Past & Future

2.1 INTRODUCTION

2.1.1 Flooding in Scotland

Flooding has significant geomorphological and socio-economic effects. In geomorphological terms flood flows are an important part of landscape evolution, creating valleys, floodplains and maintaining in-channel and riparian biodiversity (Junk et al., 1989; Bull, 1991, Raven et al., 2010). In socio-economic terms floods are an environmental hazard, as flood waters damage residential and commercial property, agricultural crops and erode pastoral land. In Scotland alone, inland flooding costs the Scottish Government an estimated £720-850 million annually (Scottish Government, 2013). Traditionally, flood and water resource managers have used statistical techniques such as flood return intervals and event probabilities to determine appropriate flood management schemes. These statistical techniques assume that the hydrological record and therefore the flow regime of a river are stationary (O'Connell et al., 2010; Salas and Obeysekera, 2014). Many studies now, however, have suggested that hydrological records are in fact non-stationary and exhibit trends and shifts (Strupczewski et al., 2001; Franks and Kuczera, 2002; Lane, 2008; Pattison and Lane, 2011;Wilby and Quinn, 2013) in high flows throughout time. There are now a growing number of studies which suggest that flooding occurs in temporal clusters and that longer term flow records exhibit periods of low flood frequency known as 'flood-poor' periods and periods of increased flood frequency known as 'flood-rich' periods (Robson et al., 1998; Black and Burns, 2002;

Robson, 2002; Werritty, 2002; Lane, 2008; Wilby et al., 2008; McEwen, 2010; Pattison and Lane, 2011; Wilby and Quinn, 2013; Raven et al., unpublished). The reasons for this non-stationary behaviour in flood frequency can potentially be attributed to changes in land management practices and land use (Potter, 1991; Stover and Montgomery, 2001; Macklin and Lewin, 2003), channel modifications and climatic variability through atmospheric circulation patterns such as the North Atlantic Oscillation and Atlantic Multidecadal Oscillation (Enfield et al., 2001; Macklin and Rumsby, 2007; Wilby and Quinn, 2013; Raven et al., unpublished).

Since the 1990s Scotland, and the UK in general, have experienced what is described as a 'flood-rich' period where there has been an increase in the frequency and magnitude of high flow events (Werritty and Leys, 2001; Black and Burns, 2002; Robson, 2002; Fowler and Kilsby, 2003). In Scotland numerous studies have investigated and discussed the concept of 'flood-rich' and 'flood-poor' periods (Smith, 1995; Steel et al., 1999; Werritty and Leys, 2001; McEwen, 2006). In 1995, Smith compiled a precipitation record dating back to 1874, which, after analysis suggested that the 1870s, 1920s and 1950s were particularly wet decades, potentially causing an increase in the frequency of high flows, and the 1930s and 1970s were considerably drier and thus had a potentially decreased frequency of high flow events. In 1999, Steel et al. took this one step further using a rainfall runoff model, IHACRES, which generated artificial flood records of up-to 126 years for 11 river basins across Scotland. The model results highlighted a regional west/east divide, potentially linked to long-term changes in the weather patterns controlling precipitation across Scotland (Wilby et al., 1997; Werritty and Foster, 1998; Black and Burns 2002), where the highest flood frequencies in the north and west were during the 1990s and the highest flood frequencies in the south east were in the 1870s. McEwen's 2010 study found a similar regional divide where the 'flood-rich' period in the 1880s and 1890s was more pronounced in the north-east, central belt and south-east than in the north and west. For Scotland as a whole the periods 1741-1750, 1791-1800, 1906-1915 were identified as 'flood-rich' periods.

2.1.2 Flood Magnitude and Frequency

The importance of flooding and the magnitude and frequency of flooding in relation to channel morphology has been well documented in the literature (Leopold and Maddock, 1953; Pickup and Warner, 1976; Wolman and Gerson, 1978; Newson, 1980; Sloan et al., 2001; Knox, 2004). Certainly, magnitude and frequency of events is a key concept across geomorphology (Wolman and Miller, 1960; Baker, 1977). This is because high flows affect the three main parameters involved in channel adjustment, explicitly: discharge, sediment transfer and erosion of the channel boundary (Thorne, 1997; Knighton, 1998; Montgomery and Buffington, 1998; Kondolf et al., 2002; Raven et al., 2010). Although river channels are constantly adjusting in response to a number of interlinking processes and feedbacks on a range of different spatial and temporal scales, it has been suggested that a channel's 'average' geometry is the product of its dominant or channel forming discharge. Early work by Wolmon and Miller (1960) suggested that the 'dominant' discharge was the discharge responsible for transporting the greatest amount of sediment over longer time scales. It was hypothesised that large floods occurred too infrequently to make significant contributions to sediment transfer and smaller more frequent flows did not have enough power to transport large volumes of sediment. Thus more frequent moderate flows were responsible for the majority of sediment transferred through the system, with the channel geometry adjusting to allow the river to convey that flow (Figure 2.1). Since then the concept of a 'dominant discharge' or 'effective discharge', its frequency and magnitude has been repeatedly discussed and investigated within the literature (Harvey, 1969; Pickup and Warner, 1976; Carling, 1988; Kochel, 1988,

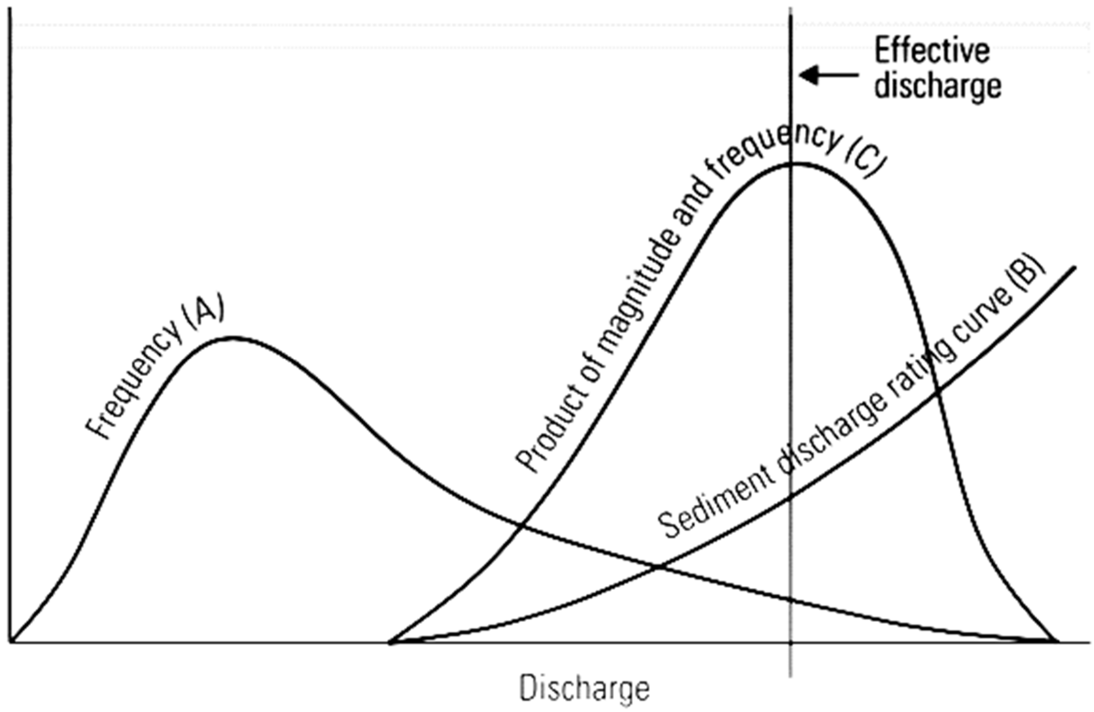


Figure 2.1 Determination of effective discharge using flow duration and sediment rating curves for a given channel. (From Wolmon and Miller, 1960; Source: Harman, 2000)

Crowder and Knapp, 2005). Wolman and Miller (1960) originally suggested that the dominant discharge was that which transported the greatest volume of sediment over longer time scales, but since then it has also been described as the flow that defines cross-sectional capacity (Wolman and Leopold, 1957) and meander wavelength (Ackers and Charlton, 1970). Bankfull discharge in alluvial rivers has often cited (Ackers and Charlton, 1970; Harvey, 1991), has a channel's dominant discharge. This is when a river's ability to carry sediment and erode is maximised (Harvey, 1969; Ackers, 1992; Knighton, 1998). The frequency of bankfull discharge however, has not been found to be consistent between river channels and indeed within the same river catchment (Pickup and Warner, 1976; Andrews, 1980; Magilligan, 1992; Knighton, 1998; Crowder and Knapp, 2005), with values ranging from 1 to 32 years (Brush, 1961; Wolmon and Miller, 1964; Harvey, 1969; Williams, 1978; Richards, 1992; Nash, 1994; Powell et la., 2006; Ferro and Porto, 2012), with the average being between 1 to 2 years (Dury, 1961; Hey, 1975; Ferro and Porto, 2012). Neller (1980) and Phillips (2002) suggested that some channels have a 'bimodal' dominant discharge or two dominant discharges. In the forested upland catchment of the Hungry Mother basin (Virginia) Phillips (2002) found smaller more frequent flows, less than bankfull, were responsible for the movement of sediment and maintaining channel morphology. Larger more infrequent floods (with a recurrence interval measured in decades) were responsible for shaping the banks of the channel. Lenzi et al., (2006) came to the same conclusions when looking at sediment loads in the Italian Alps. Floods with a return interval of 1.5 to 3 years were found to be responsible for maintaining channel form (pool depth and steepness) and floods with a return interval of 30 to 50 years were responsible for macro-scale changes such as channel width and planform adjustments. The body of work described above demonstrates the complexity of determining and defining a threshold discharge for channel change and the number of factors (geology, soil permeability, land use, catchment size, and channel type) that need to be considered when selecting a return interval.

2.1.3 Channel Adjustment

River channels will frequently change and adjust to a variety of internal and external forces, but through a self-regulating feedback system manage to maintain a stable state both spatially and temporally (Bull, 1991; Knighton, 1998). This dynamic equilibrium or fluvial equilibrium means that a river will adjust to small changes in its hydrological and sediment regime and then recover over time back to its original state as long as these changes remain within set boundaries or thresholds. If the disturbance causes a critical threshold to be crossed, then the river will recover to a stable state but operate around a new equilibrium position (Figure 2.2).

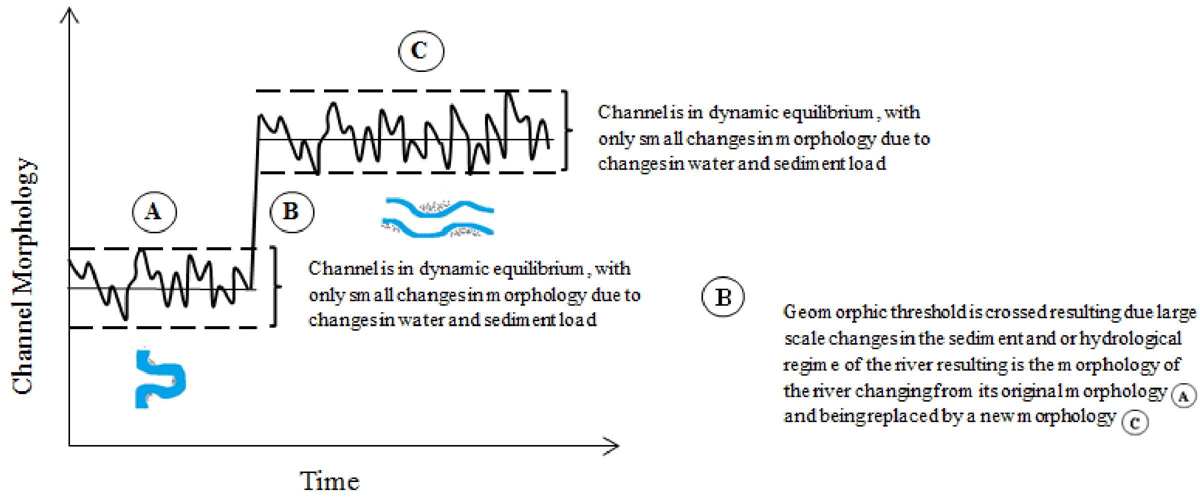


Figure 2.2: Concept of dynamic equilibrium and threshold behaviour in river channels (adapted from Werritty, 1997 and Sear and Newson, 2010)

Rivers can also be in a state of 'disequilibrium' whereby the recovery or 'relaxation' time between disturbances is shorter than that required for the river to recover and restabilise resulting in the planform of the river being transient and constantly adjusting, making it more prone to chaotic behaviour (Werritty, 1997; Sear and Newson, 2010). This type of behaviour can also be a result of a positive feedback within the system where one disturbance leads to another disturbance amplifying the river's first adjustment in the same direction (Renwick, 1992; Werrity, 1997; Hooke, 2007; Newson, 2002).

As climate change could potentially decrease the number of days between flood events and reduce the time available for rivers to return back to their original state, there is the potential for a threshold to be crossed and thus the river to establish a new equilibrium. This concept of thresholds and channel change has been discussed in the literature (Schumm, 1973; 1979; Bull, 1991; Werritty, 1997; Knighton, 1998). As mentioned above, a geomorphic threshold is crossed if a landform's morphology is altered permanently so that its shape alters slightly around a different 'mean' shape than it did previously. In the context of a river these changes could be changes in planform, channel width and depth or slope. These changes can occur over a range of different timescales (abrupt or gradual) and can be extrinsic in nature (result of external force) or intrinsic in nature (result of internal force) (Schumm, 1979; Bull, 1991). The direction of change and ease at which a channel will adjust to changes in discharge and sediment load are a result of channel and/or landscape sensitivity (Brunsden and Thornes, 1979; Brunsden, 2001). A river channel can adjust a number of different parameters (depth, width, slope) to convey larger or smaller volumes of water and sediment, known as a channel's degrees of freedom (Hey, 1978; Knighton, 1984; Gregory, 1987; Downs and Gregory, 1993) these are shown in Figure 2.3.

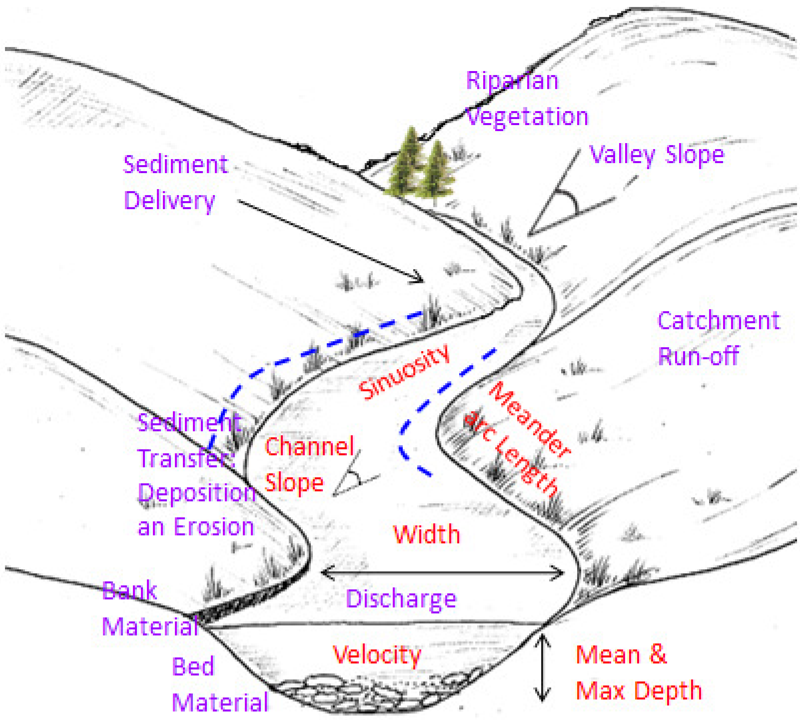


Figure 2.3: Degrees of freedom and process drivers of channel change. Process drivers are shown in purple and degrees of freedom are shown in red. Degrees of freedom include: channel width, mean and maximum depth, channel slope, mean channel velocity, planform sinuosity and meander arc length. Process drivers of channel change include: discharge and catchment run-off, sediment delivery and transfer, bed material characteristics, bank material, valley slope and riparian vegetation (Sear and Newson, 2010) (adapted from Raven et al., 2010)

Channel adjustments can occur due to autogenetic (within channel) and allogenic (outside channel) influences (Lewin, 1977; Down and Gregory, 1993), and the channel's response or sensitivity to these changes will depend on a variety of different factors such as geology (bedrock or alluvial), planform (meandering or wandering) and current human modifications (straightened or natural). Brunsden and Thorne (1979) suggested that a transient-form ratio could be used to identify landform sensitivity to change:

$$TF_r = \frac{\text{mean relaxation time}}{\text{mean recurrence time of events}}$$

If unity is achieved (i.e. ratio is equal to 1) then after a disturbance the river will maintain its current form. Conversely, if the ratio is less unity (i.e. less than 1) then the river will adjust slightly before restabilising to maintain its new state, and if the ratio is greater than unity (i.e. greater than 1) then the river will be in state flux or disequilibrium where-by the frequency of disturbances is greater than the time required for the river to recover and restabilise. Despite the difficulty in stipulating the mean relaxation and recurrence time of events it (the model/ the equation) does provide some indication of the stability or 'robustness' of the river system to a certain disturbance and its ability to regain equilibrium again post-disturbance. However, it is also important to consider that the sensitivity of a river channel and its 'robustness' to change. Thus the adjustments made by the river as a result of change or disturbance may vary as a result of differences in antecedent condition (Newson, 1980), channel coupling (Harvey, 1994; Hooke, 2003; Reid et al., 2007), as well as land use and land cover (Knox, 1977; Knox, 2000; Macklin and Lewin, 2003) and human modification (Gregory, 2006).

When the sensitivity of Scottish rivers to hydrological changes over time was investigated (Ley and Werritty, 1999) and reviewed (Werritty and Leys, 2001) it was concluded that Scottish rivers were on the most part 'robust' and thus have the ability to absorb potential hydrological and sediment transfer changes with only small adjustments to their morphology (Werritty and McEwan, 1997; Werritty and Leys, 2001). Several reasons for the ‘robustness’ of Scottish river channel to morphological adjustment include: a lack of mining operations injecting large volumes of sediment into rivers, rivers tending to be only weakly coupled to their valley sides and a glacial history resulting in relatively coarse bed material or the river being incised into the underlying bedrock (Werritty and Leys, 2001). As a result studies investigating channel change in Scotland have tended to focus on historical changes in channel planform (McEwan, 1994; Leys and Werritty, 1999), medium to long term channel adjustments (Winterbottom, 2000) and the impact of large flood events on channel morphology (McEwen and Werritty, 1988; Bryant and Gilvear, 1999; McEwan and Werritty, 2007). Fewer studies have considered the effect of a change in the frequency of bankfull floods or dominant discharge which are important for maintaining channel planform and geometry, floodplain connectivity and a high ecological integrity (Junk et al., 1989; Poff, 2002; Gordon et al., 2004; Doyle et al., 2005). Although bankfull flows will not cause large scale changes in channel morphology to occur changes in magnitude and frequency of these flood flows have been found to be important for riverine ecology (Clausen and Biggs, 1997; Tockner et al., 2000). Thus changes in the frequency of bankfull flows through-out time or with future climate change could have important implications for aquatic ecology. This is because floods help to rejuvenate river ecosystem by maintaining physical and ecological habitat structure and function (Poff, 2002). Therefore, when a river’s hydrological regime is altered the naturally destruction and rejuvenation of river habitat is impaired.

When the concept of a dominant discharge and channel change is considered in relation to changes in the frequency of flood events it would appear that river channels would go through periods of increased geomorphic activity (‘geomorphologically-rich’ periods) followed by periods of decreased geomorphic activity (‘geomorphologically-poor’ periods). This infers that the dominant discharge would occur more often during 'geomorphologically rich' periods and less often during 'geomorphologically-poor' periods. As future climate change is predicted to increase winter river flows across Scotland, in some areas by over 50% (Kay et al., 2011), this could potentially mean that Scottish rivers will be more active than they have been previously, and move towards a "super-rich geomorphic state" compared to past conditions. Periods in the past where river reaches have been less geomorphologically active will be more geomorphologically active, and periods where river reaches have been more geomorphologically 'benign' will have increased activity, thus Scottish river channels will enter a period of evolution as they adjust to this new regime. This would have important implications for future management of rivers in terms of flood risk, bank and sediment management, channel restoration and planning. Previous studies have predominately focused on modelling back in time to find trends and step changes in flooding across the UK (Steal, 1999; McEwen, 2010). Here, long (over 50 years) historical discharge records are investigated to see if these trends, fluctuations and step-changes in flood frequency are present in the flow records of six rivers across Scotland and thus suggesting that geomorphic activity within Scotland may well be non-stationary. The potential impact of future climate change on any fluctuations, trends and step-changes is also considered.

2.2 METHODS

In Scotland river water levels are monitored daily at 392 locations by SEPA. The length of these records varies from over 80 years to less than 15 years. The longest record is of the River Dee at 85 years. Rivers were selected that had a record length of greater than 50 years, had no gaps within their record, and as far as possible were well distributed spatially across Scotland presenting hydro-climatic regions. The exception to these rules was the River Earn where there is no data from the 1st January 2003 to 31st December 2003. It was decided that this would not be an issue for the analysis here because none of the surrounding local rivers which have data for 2003 experienced significant flood peaks during this year. Records which were shorter than 50 years were considered too short (Robson, 2002) to detect trends, shifts and decadal variations in flood frequency. A POT (peaks over thresholds) flood series was constructed using daily flow data from six rivers across Scotland (River Dee, Woodend; River Spey, Boat O'Garten; River Findhorn, Forres; River Earn, Killkell Bridge; River Clyde, Sills of Clyde; River Almond, Almondbank) (Figure 2.4). The recorded daily flow from the data sets represents the mean flow on that day. This was obtained from the National River Flow Archives. The mean daily flow was considered suitable for this study as all the gauging sites were located in catchment greater than 170 km^2 in size. Flood peaks would therefore be expected to appear in a mean daily flow record, unlike in smaller catchments which are much more sensitive to changes in flow with flood peaks only lasting several hours..

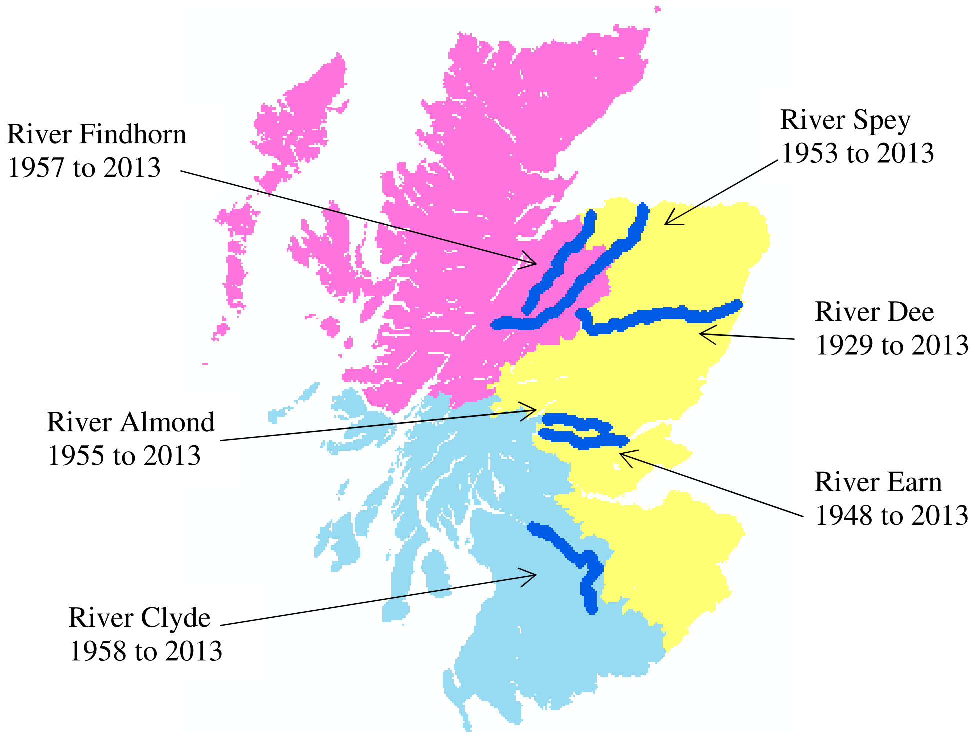


Figure 2.4: Location of rivers used in this study within Scotland and record length. Blue represents a west of Scotland catchment, yellow an east of Scotland catchment and purple a north (highland) catchment based on UKCIP's (2002) breakdown of the UK for predicting climate change.

As the aim here was to examine the frequency of floods that were most likely to contribute to channel instability and increased geomorphic activity, the thresholds for flood peaks was taken to be a flood that had a return interval of two years. Although the frequency of flows responsible for significant geomorphic activity has been shown to vary between 1.1 years to 12 plus years depending different catchment characteristics such as soil permeability (Harvey, 1969; Leopold, 1994; Petit and Pauquet, 1997; Surian, et al., 2009; Ferro and Porto, 2011), for gravel bed rivers, like those found in many parts of Scotland, it is generally accepted to be between 1.5 and 2.8 years (Harvey, 1969; Leopold, 1994; Ferro and Porto, 2011). Here a return interval of two years was selected for ease of calculation and to ensure there was enough flows within the data for any trends or shifts to be established. Thus for this study the more frequently the river exceeds this flow then it is assumed the more geomorphologically active the river was during that given period. The 1:2 year flow of each river was calculated using the Log-Pearson Type III Distribution method described by Oregon State University (http://streamflow.engr.oregonstate.edu/analysis/floodfreq/). Although a flow with a return interval of two years may not be the exact return interval for bankfull discharge for each river it provides a consistent measure to allow the activity of the different Scottish rivers to be assessed over time.

Time series plots were created for each river showing the number of flows per year over 1:2 year flood flow and the number of days between 1:2 year flood peaks to look for any general trends or shifts within the flow records. A linear trend line and LOESS smoothed curve were added to each plot to aid in the identification of any trends and shifts within the flow records. Mann-Kendall tests (a ranked based non-parametric test) were completed on each river to assess whether any of the data sets displayed a significant upwards or downwards monotonic (gradual change over time in one direction) trend in the number of POT floods annually or number of days between POT events within the flow data sets. There had to be a minimum of seven days between flood peaks to ensure it was a single high flow event and not multiple peaks part of the same event. This was done using the 'Kendall package' (Hipel and McLeod, 1994) in R Studio version 0.97 (R Development Core Team, 2012).

To investigate if there had been any significant shifts in the number of POT flows (1:2 year flows) or the number of days between POT events within the flow records, a distribution-free CUSUM was undertaken using R Studio version 0.97 (R Development Core Team, 2012). If a significant shift was present this would correspond with the suggested 'flood-rich' and 'flood-poor' period trend sited elsewhere in the literature (Robson et al., 1998, Robson, 2002; Pattison and Lane, 2011; Wilby and Quinn, 2013).

A distribution-free CUSUM was selected as it detects shifts within a data series which cannot be explained by natural variability and it allows for the identification of when these shifts occurred (Osanaiye and Talab, 1989; Jessop and Harvie, 2003). It is a ranked based, non-parametric test meaning it does not assume the data are normally distributed, as is the case with most hydrological data (Robson et al., 1998). The median value is taken away from each observation in the entire data series (Chiew and McMahon, 1993; McGhilchrist and Woodyer, 1993) and then the values cumulatively added together to display a general upwards or downwards trend over time. The test statistic is the maximum vertical distance between the CUSUM path and the standard deviation, with significance levels being determined using the Kolmogorov-Smirnov test algorithms (McGilchrist and Woodyer, 1975).

To assess the potential impact of climate change a 'climate change enhanced flow record' was modelled. To create this flow record, daily winter (December to February) flows for the current record were amplified by the percentage increase in 1:2 year flows outlined by the Centre for Ecology and Hydrology (Kay et al., 2011) under medium emissions scenarios by 2080. The steps used to create a climate enhanced flow record can be found is Figure 2.5. The percentage increase was only applied to winter flows as current climate predictions outlined by UKCIP09 (Jenkins et al., 2009) make no specific mention of the changes to spring, summer and autumn flows, as these are not expected to increase considerably, if at all. Using this approach, however, to develop a climate enhanced flow record assumes that any increase in the magnitude and frequency of 1:2 year flood flows would occur between December and February and does not take into account any seasonal shifts which may occur with climate change such as changes in snow accumulation in upland catchments (Kilkus et al., 2000; Bronstert, 2002; Baggaley et al., 2009). Although studies such as that by Baggaley et al., (2009) for the River Dee (Aberdeenshire) have shown a shift towards an increase in spring flows and a decrease in summer flows linked to changes in snow melt flooding, others such as Hannaford and Buys (2012) found that the greatest decrease in flows occurred in spring (March – May) when looking changes at seasonal flows in a wide variety of river catchments across the UK. A similar trend was seen in Lisuthian rivers, whereby the timing of high flows events has moved from April to March and even February due decreasing snow accumulation in the upland catchments (Kilkus et al., 2000). No adjustment is made to account for the predicted decrease in summer rainfall (Hulme and Jenkins, 1998) which may result in a decrease in the frequency of summer flooding in this analysis. The decision not to decrease summer flows was taken because studies have shown that changes in summer flows are variable and less significant (Petrow and Merz, 2009; Hannaford and Buys, 2012). Hannaford and Buys' (2012) study for example, investigating the impact of climate change on seasonal river flows found 'no compelling evidence' that summer run-off rates were likely to decrease with climate change. Summer flows were also found to show the smallest difference in flow variation of any of the four seasons (Hannaford and Buys, 2012). The effect of climate change on autumn flows is also conflicting within the literature. Climate models investigating the changes in precipitation and run-off have found that the magnitude and direction of changes in precipitation changes regionally with no strong indication for a seasonal shift in autumn and summer run-off patterns (Barnett et al., 2005). Due to the different seasonal responses to the flow regimes of individual rivers in spring and autumn depending on catchment characteristics, the decision was taken just to focus on the increase in winter flows with climate change in this study, as much of investigation into the effect of climate change on precipitation and run-off in the literature have predicted an increase in winter flooding. However, this does mean that in this study it assumes that the seasonal changes in precipitation and run-off will remain constant with climate change. Therefore, the study does not take into account the complex hydrological changes which may occur in an upland Scottish catchment with climate change due to changes in snow accumulation melt in upland river catchments. Instead, the results here show the significant impact that change in winter precipitation and run-off with climate change will have on the frequency and pattern in the occurrence of 1:2 year magnitude floods. A medium emissions scenario was selected to investigate the patterns in the data, and an assumption was made that the same patterns would appear under both a low and high emissions scenario, although damped in a low emission scenario and heightened under a high emissions scenario.

The report by the Centre of Ecology and Hydrology (CEH) outlines a catchments sensitivity to increases in flood peaks as a result of predicted changes in climate at four return intervals (2, 10, 20 and 50 years) for different emission scenarios (low, medium, high) and time intervals (2020, 2050, 2080) using UKCIP09 data. The predicted climatic changes along with catchment characteristics (geology, soil permeability and land use), are considered to assess the predicted response of peak flows into nine categories from highly-damped (low sensitivity to change) to highly-enhanced (high sensitivity to change). Although the percentage increase in flow predicted by the CEH report refers primarily to the magnitude of 1:2 year flood peaks the percentage increase has been applied to all winter flows (December to February), as current predictions on future climate change (Jenkins et al., 2009) suggest that there is a 90% probability of increased winter wetness. Using the percentage increase in flow generated by CEH was considered more accurate than using the predicted percentage increase in rainfall. This was because a predicted increase in river flow considers the river catchments' ability to respond to an increase in rainfall, whereas using increasing rainfall would assume a linear relationship between increasing rainfall and river flow, which in reality would not be the case (Goodrich et al., 1997; Sivapalan et al., 2002; Kokkonen et al., 2004). The percentage increase in flow was taken at the 90% probability level (i.e. there is a 90%

Creating Climate Enhanced Flow Record

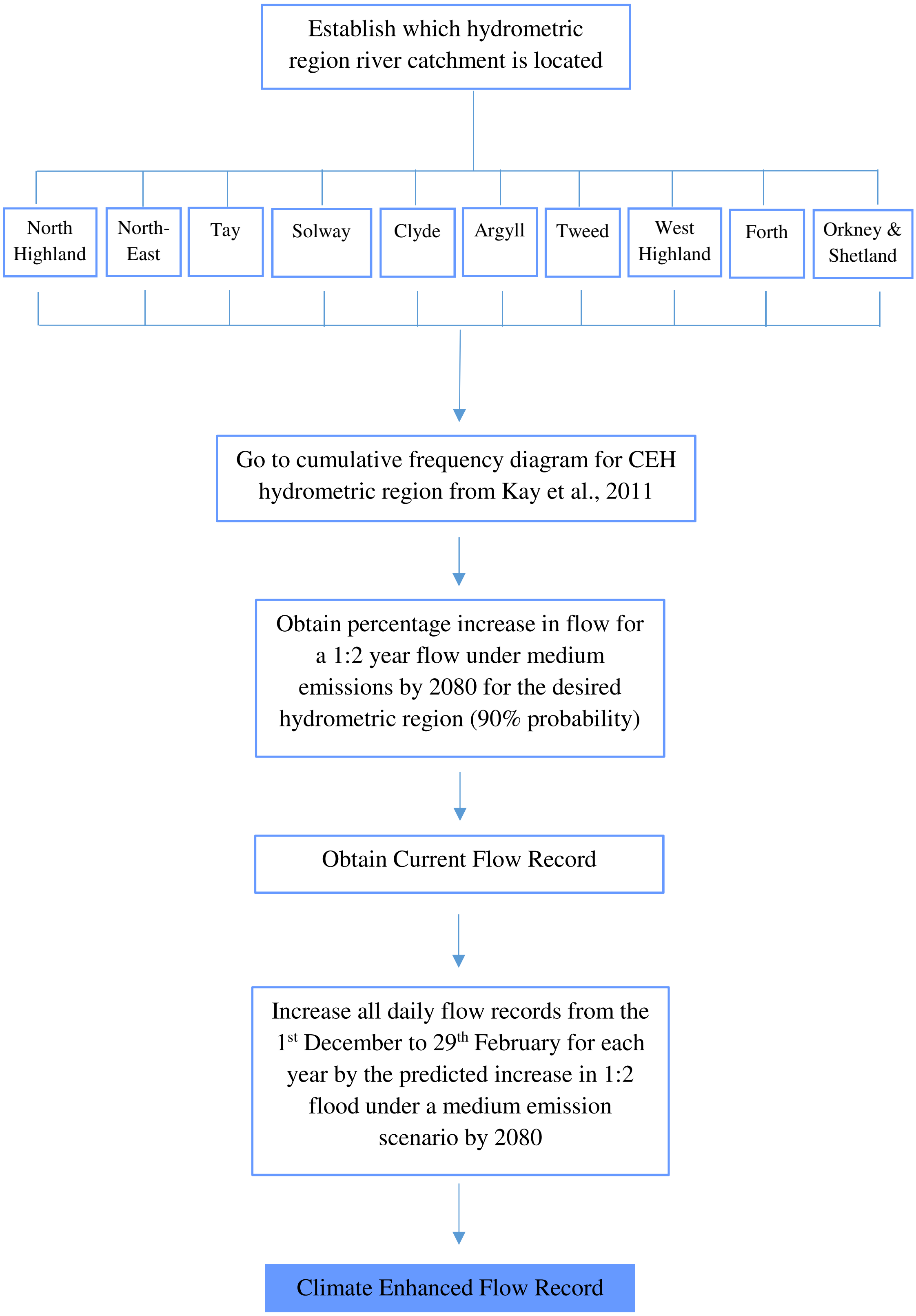


Figure 2.5: Flow diagram of method used to create a climate enhanced flow record.

chance that the increase in flow will not be greater than that value) and represents a worst-case scenario approach. The number of days between successive 1:2 year flood peaks and also the total number of 1:2 year flood flows were then recalculated using the climate enhanced flow record to investigate the impact of climate change on channel activity.

The Mann-Kendall and distribution-free CUSUM statistical tests were then repeated on the climate enhanced flow records to see if the same trends were identified. The non-parametric Mann U Whitney test was completed using R Studio version 0.97 to see if there was a significant difference between the number of flood flows and number of days between flood peaks for the current flow record and climate change enhanced flow record. To explore the effect of increased flood activity between potentially less-geomorphologically active periods and more-geomorphologically active periods, and the potential impact of climate change on geomorphic activity, the number of days particles of a given size are mobilised at each gauging site was analysed. SEPA's (Scottish Environmental Protection Agency) Scottish River Network, a spatially distributed river network of centre-lines (as depicted on a 1: 25,000 map), with a database which contains modelled channel data at 50m intervals was used to obtain slope values and channel width values for each of the gauging station sites. The critical stream power required to move pebbles of the sizes typical of Scottish gravel bed rivers (22 mm, 32 mm, 45 mm, 63 mm, 90 mm and 128 mm) was then calculated using Ferguson's 2005 method for calculating the critical stream power to move grains of any size on a mixed gravel-bed:

$$\omega_{ci} = 0.113 D_b^{1.5} \log\left[\frac{0.73}{S}\left(\frac{D_i}{d_b}\right)^{0.4}\right]\left(\frac{D_i}{d_b}\right)^{0.6}$$

Where D_i represents the size of grain entrained by the flow in meters, D_b/d_b is relative roughness (the representative grain size for the river bed as a whole in meters), *S* is the channel slope in meters, *b* which is hiding factor at 0.6, *k* is Karman's constant (logarithmic velocity profile) at 0.4, 0.73 is the sediment density (*R*) and 0.113 being the constant *a*.

Ferguson's 2005 equation for critical stream power was used because unlike Bagnold's 1980 equation, it does not require a depth value and takes into consideration hiding and protrusion effects making it more realistic for natural gravel and cobble bed rivers. As the matrix of river bed is unknown it is assumed, in this study, that the pebble size selected for each river was the D_{50}. The specific stream power was calculated for every daily flow record for each river using following equation (Thorne et al., 2010):

$$\omega = \frac{\gamma \cdot Q \cdot S}{W}$$

where with Q is the discharge (m^3 s^{-1}), W the width of the water surface (m) and S is the longitudinal slope (m m^{-1}), q the fluid density (kg m^{-3}) and g the acceleration due to gravity (m s^{-2}). Each flow record was then filtered to remove all flows which would not have been high enough to move the selected substrate size. The substrate size selected for all rivers was 63mm except the Spey where 22mm was selected. A 63mm substrate size was selected because it was recognised as an important substrate size for salmonid habitats (Hendry and Cragg-Hine, 1997, 2003; Armstrong et al., 2003). River beds with habitats composed of pebbles with a substrate size between 16mm and 64mm for *Salmo salar* (Atlantic salmon) and between 10mm and 90mm for *Salmo trutta* (Brown trout) have been identified as prime nursey habitat with the literature (Bardonnet and Heland 1994; Hendry and Cragg-Hine, 1997; Armstrong et al., 2003; Moir and Pasternack, 2010). More frequent disturbance to these habitats may result in a reduced egg-to-fry survival rate (Schneider, 2011). This may then also in the longer term have a knock-on impact on the Scottish economy. In 2004, the Scottish Government estimated that freshwater angling had an annual output of 100 million, which support 2800 jobs and generated 50 million in wages. Furthermore, salmonids are required for the critically endangered freshwater pearl mussel to complete its life cycle (Skinner et al., 2003). Any decline in salmonid population would therefore potentially result a decline in freshwater pearl mussel populations. Thus, any significant decline in fish populations, could have significant biological and economic impacts. It should be noted that this study will not provide an indication of the impact of climate change on salmonid habitat. The biological and economical significance of salmonids instead provides justification for selecting a 63mm to investigate patterns in bedload patterns between the different rivers selected in this study. However, this method of looking at frequency of different pebbles sizes could be applied to sites known to contain suitable fish habitats to investigate any future changes in bed disturbance with climate change. This pebble size was not used in the River Spey because a 63mm pebble had never moved and 32 mm pebble had only moved seven times. Therefore, to ensure enough data was available to look for patterns a pebble size of 22mm was selected. This pebble size was predicted to have moved 98 times (Table 2.1). The selection of this pebble size was still deemed geomorphologically relevant as 22mm pebble has been identified as the median grain size for salmonid spawning habitats (Moir et al., 1998; Armstrong et al., 2003). This is particularly relevant in the Spey which has been designated a Special Area of Conservation (SAC) and supports one of largest salmon populations in Scotland due to it high quality spawning gravel habitats (River Spey Catchment Management Plan, 2016). In summary, in the Almond, Clyde, Dee, Findhorn and Earn a 63mm pebble was used and for the Spey 22mm pebble. This was repeated for the ‘climate enhanced flow record’. Although increased flow magnitude with climate change could bring about a coarsening of the river bed and a change in the D_{50} of a river reach, is not considered relevant for the purposes of this study. This is because, this study is looking at how often a river would have the power to move a pebble of a certain size, in this case 63 mm or 22 mm, pebble i.e. a theoretical D_{50} not actually D50 of a river reach. Here it has been assumed that the river would still theoretically have enough power to move 63mm or 22 mm pebble even if a coarsening or change in the river bed occurred with an increased frequency of winter flood events. For ease of calculation the sizes selected to investigate the number of times a pebble has moved were the same as used in a Wolman pebble count (Wolman, 1954). The CUSUM tests and Mann-Kendall tests were carried out on the current flow records and a climate enhanced flow record, and a Mann-U Whitney test completed to see if there was a significant difference between pre- and post- climate change scenarios.

Table 2.1: Number of Times a Pebble of a Given Size Has Moved since Flow Record Began

	Current Flow Record						*Climate Change Enhanced Flow Record*					
Pebble Size (mm)	**Almond (1955)**	**Clyde (1957)**	**Dee (1929)**	**Earn (1948)**	**Findhorn (1958)**	**Spey (1951)**	**Almond (1955)**	**Clyde (1957)**	**Dee (1929)**	**Earn (1948)**	**Findhorn (1958)**	**Spey (1951)**
16	12,017	10,469	17,948	11,885	10,340	641	12,556	11,213	20,759	12,806	11,237	956
22	7,975	6,363	9,931	7,102	7,757	98	8,677	7,160	12,408	8,338	9,271	190
32	4,187	2,764	4,064	2,861	3,984	7	4,772	3,483	2,000	3,815	5,222	14
45	1,818	1,027	1,278	760	1,862	1	2,285	1,484	1,920	1,271	2,758	1
63	703	264	338	115	657	0	993	467	520	285	948	0
90	166	32	50	7	157	0	246	86	109	24	263	0
128	31	2	3	0	32	0	55	7	7	2	54	0

Pebble size selected for each river highlighted in yellow. The starting year of each flow record is shown in brackets.

2.3 RESULTS

2.3.1 Trend Analysis and Step-Changes

The number of days that a 1:2 year flow has been exceeded on each of the six rivers being investigated is shown in Figure 2.6. Overall visual assessment of the results shows that there appears to be slight up-wards trend in the occurrence of 1:2 year floods in all rivers except the River Dee, in which there is noticeable downward trend in the occurrence of 1:2 year floods. Mann Kendall tests (Table 2.2) carried out on each river showed that there was a statistically significant upwards trend for the rivers Clyde, Findhorn and Spey. No statistically significant trends were found in the Dee, Earn or Almond. Record length may, in part, provide an underlying explanation for these results as records for the Clyde and Findhorn start in 1957 and 1958 respectively. This could mean these records are missing the potentially higher flows occurring during the 1950s, resulting in flow records going from less high flows events to more flows events rather than having a low, high, low pattern as suggested elsewhere in the literature (Robson et al., 1998b; Pattison and Lane, 2011; Wilby and Quinn, 2013). The LOESS smoothed curve suggests that in the Almond and Earn there was a slight dip in the occurrence of 1:2 year floods between around 1970 and 1980, which would tie in with the suggestion that 1970 and 1980 was a ‘flood-poor’ or a less-geomorphologically-active period across the UK in general. The Clyde, Findhorn and Spey show no distinct dip around the 1970’s and 1980’s and instead show a much more linear upwards trend. The Dee shows only a very slight dip around 1970 and 1980 but generally shows a more stationary pattern in flood flows throughout its flow record. The distribution-free CUSUM (Table 2.3) completed on each river only found a significant shift in the occurrence of 1:2 year floods in the River Earn. On the Earn only one shift was found to have occurred around 1957 where the mean number of floods per year went from 2 (1948 to 1956) to 1.16 (1957 to 2010).

The slight dip seen on the Almond can therefore be assumed to be due to natural variability.

Table 2.2 Mann-Kendall Results for each River for the Number of Times 1:2 year Flow Exceeded and Number of Days between 1:2 year Flood Peaks

	Number of Times 1:2 year Flow Exceeded			*Number of Days between 1:2 year Flood Peaks*		
River	**Z - Value**	**Upwards Trends (p value)**	**Downwards Trend (p value)**	**Z - Value**	**Up-wards Trends (p value)**	**Downwards Trend (p value)**
Almond	0.6084	0.2715	0.7286	-0.7581	0.7758	0.2242
Clyde	1.7037	0.0442	0.9558	-1.3114	0.9051	0.0949
Dee	-1.7995	0.9640	0.0360	1.3906	0.0822	0.9178
Earn	0.1747	0.4306	0.5694	-0.8318	0.7972	0.2028
Findhorn	2.7384	0.0031	0.9969	-1.3401	0.9099	0.0901
Spey	2.2623	0.0118	0.9882	-1.4123	0.9211	0.0789

Significant results shown in red. Significant at 95% confidence level

Figure 2.7 shows the number of days been successive 1:2 year flood peaks. The Clyde, Findhorn and Spey all show a potential downward trend in the number of days between floods, whereas the Dee shows a slight upwards trend and the Almond and Earn show no trend. This suggests that in the Clyde, Findhorn and Spey that 1:2 year floods are occurring more often than they have in the past. The River Dee shows the reverse trend in that the number of days between flood peaks is increasing, thus suggesting 1:2 year flows have become less frequent, whereas in the Almond and Earn it has overall been fairly consistent throughout the flood record. Mann-Kendall tests carried out on each river showed that there was no statistically significant downwards or upwards trend for any of the rivers (Table 2.2).

The LOESS smoothed curve suggests that in the River Almond and Earn there was an increase in the number of days between floods around 1980, which again would tie in with current thinking that 1980s were a drier ‘flood-poor’ period. The River Clyde, Findhorn and Spey shows no change around the 1980s and instead just show a general decrease in the number of days between floods. In contrast the River Dee actually shows an increase in the number of days between 1:2 year flood peaks suggesting that floods are occurring less frequently now than they have done in the past. The CUSUM analysis found that there were significant shifts in the number of days between flood peaks in all rivers (Table 2.4 and Figure 2.8). The River Spey and River Findhorn show only one step change around 2000, with both showing a decrease in the mean number of days between floods going from 404 to 153 and 453 to 171 days respectively, suggesting a marked change in the frequency of 1:2 year floods over the last 15 years. This slightly contradicts current thinking which suggests that the 'flood-rich' period started in the late 1980s when a series of high magnitude floods occurred across Scotland (Black and Burns, 2002). Equally it could be that the 'flood-rich' period which started in the around 1990 has been further enhance in these rivers since 2000 due to climate change or changes in land management practices. The most southerly rivers; the Earn, Clyde and Almond, all show three significant shifts within their record, which support the concept of going from a 'flood-rich' to 'flood-poor' and back to 'flood-rich' periods over the last 55 to 65 years. The two shifts occurred on the Earn in 1963 and 1997 with the mean number of days between flood peaks going from 249 to 946 and back to 25. In the Almond the first shift occurred in 1963 and the second in 1988 with the mean number of days between floods going from 159 to 573 to 194.

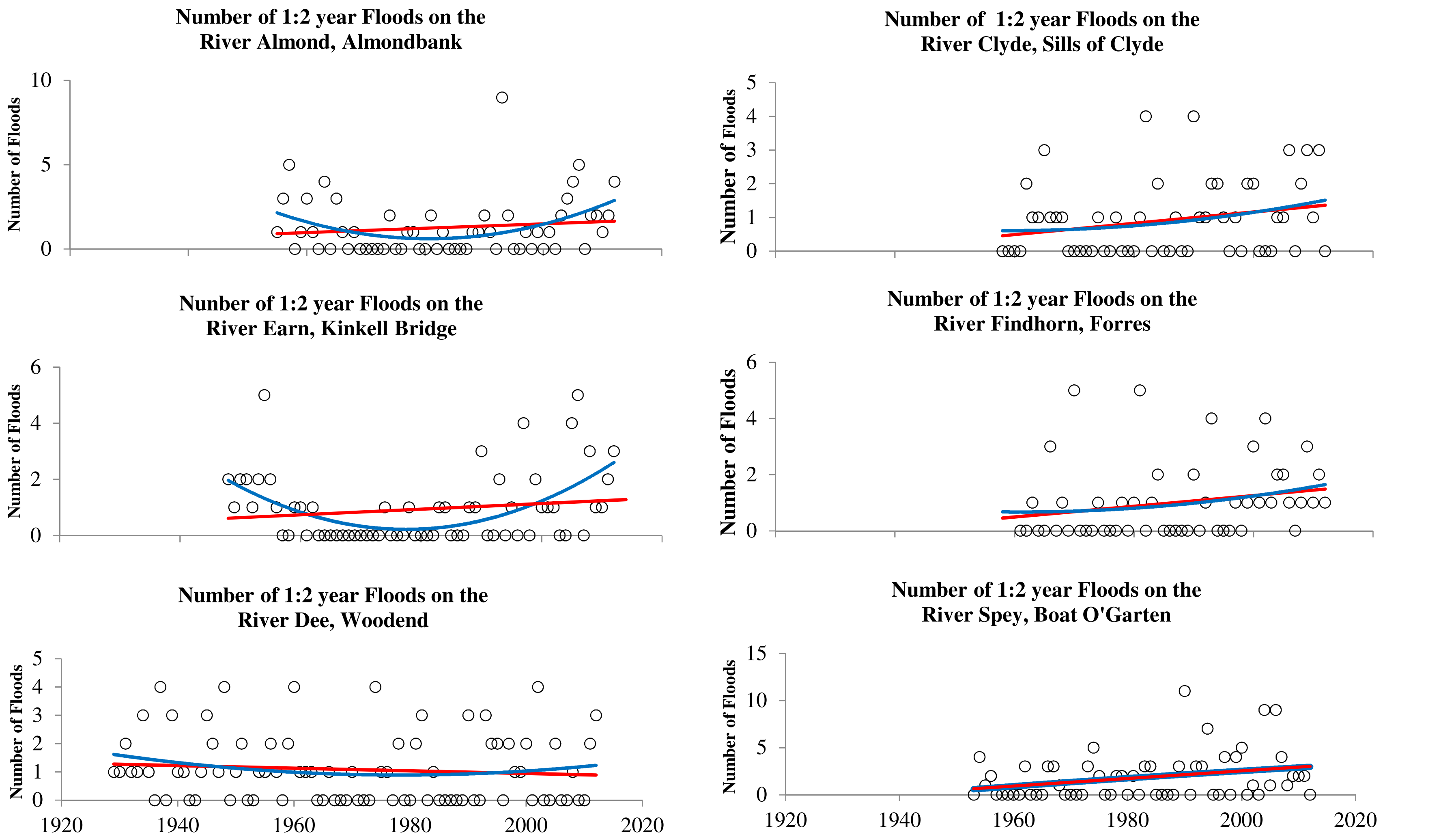


Figure 2.6: Changes in the number of 1:2 year flood flows per year for all six catchments. The graphs include a regression line shown in red and local-weight smoothing curve (LOESS curve) shown in blue.

Table 2.3 CUSUM Analysis: Number of 1:2 year Flood Flows

		Change Point 1					*Change Point 2*				
River	**Record Length (years)**	**Start Year**	**End Year**	**Mean**	**St. Dev.**	**p-value**	**Start Year**	**End Year**	**Mean**	**St. Dev.**	**p-value**
Almond	58	1955	2012	1.21	1.702	<0.0001					
Clyde	55	1958	2012	0.89	1.086	<0.0001					
Dee	84	1929	2012	1.04	1.196	<0.0001					
Earn	64	1948	1956	2.00	1.225	<0.0001	1957	2012	0.7	1.15	0.0088
Findhorn	55	1957	2012	0.94	1.325	<0.0001					
Spey	60	1953	2012	1.86	2.509	<0.0001					

Table 2.4 CUSUM Analysis: Number of Days between 1:2 year Flood Peaks

		Change Point 1				*Change Point 2*				*Change Point 3*				*Change Point 4*			
River	**Record Length (years)**	**Start Year**	**End Year**	**Mean**	**p-value**	**Start Year**	**End Year**	**Mean**	**p-value**	**Start Year**	**End Year**	**Mean**	**p-value**	**Start Year**	**End Year**	**Mean**	**p-value**
Almond	58	1956	1963	159.5	<0.0001	1965	1988	573.0	0.0058	1988	2013	194.4	0.0067				
Clyde	55	1962	1967	187.4	<0.0001	1974	1990	647.3	0.0202	1990	2011	228.7	0.0110				
Dee	84	1930	1963	256.1	<0.0001	1966	1993	599.5	0.0040	1993	2002	214.8	0.0091	2005	2013	543.00	0.0326
Earn	64	1948	1963	249.1	<0.0001	1974	1995	946.3	0.0120	1997	2013	25.8	0.0055				
Findhorn	55	1966	1999	453.1	<0.0001	2000	2012	171.4	0.0217								
Spey	60	1954	2000	404.1	<0.0001	2000	2010	153.5	0.0049								

In the Clyde the first shift occurs around four years later than the Almond and Earn in 1967 and the second around 1990 with the mean number of days between floods going from 187 to 647 to 288. The River Dee shows four shifts in the number of days between flood peaks, possibly because it is the longest record. Two 'flood-rich' periods were identified between 1930 and 1963 and 1993 to 2002 and two 'flood-poor' periods between 1966 and 1993 and 2003 to 2013 with mean values of 256, 599, 214, and 543 respectively. The 'flood-poor' period occurring around 2005 is particularly interesting as there is marked decrease in the number of days between floods during this period on the River Spey only the other side of the Cairngorm mountain range. This section emphasises a new form of analysis of floods in Scotland over time where by the frequency of 1:2 year values of a flow, deemed to be geomorphologically relevant, are analysed emphasising the frequency parameter in the classic magnitude-frequency framework within geomorphology.

2.3.2 Trends and Step Changes with Climate Change

To investigate the change in the occurrence of 1:2 year floods with future climate change (medium scenarios for 2080) the numbers of flood events per decade pre- and post-climate change scenarios were identified. The general pattern of wetter decades interspersed with drier decades remains (Figure 2.9) but many of the drier, traditional 'flood-poor' periods would become significantly wetter, for example the number of 1:2 year flood flows that occurred during the 1970's and 1980's could increase by 600% and 350% respectively in the River Earn under future climate change predictions. The Clyde and Earn have the biggest overall percentage increases in the occurrence of 1:2 year flood flows at 163% and 215% respectively. This equates to an increase from 46 to 121 floods in the Clyde and 52 to 164 floods in the Earn.

The more northerly rivers of the Dee, Spey and Findhorn and more easterly Almond tend to show a lower overall increase in the occurrence of 1:2 year flood flows with Figures of 42%, 78%, 51% and 66% respectively. Mann U Whitney tests comparing the number of 1:2 year floods pre- and post- climate change confirmed that the effect of climate change would be significant (Table 2.5). Mann-Kendall tests showed there was no significant downwards trend in any of river but there was a significant upwards trend in the Clyde and Findhorn (Table 2.6). The CUSUM analysis (Table 2.7) also only found a significant shift in the Clyde and Findhorn and in both cases the shift in a significant increase in the number 1:2 year flood flows per year in the Clyde from 1.5 to 4.1 and 1.39 to 3.4 in the Findhorn. This is compatible with the Mann-Kendall results, which suggested an upwards trend for both rivers. Interestingly the pre- climate enhance record for the River Earn showed one shift in the number of occurrence of 1:2 year floods which does not occur in the climate enhance record.

Table 2.5 Mann U Whitney Test Results showing the Significant difference between Past Flow Records and Climate Change Enhanced Flow Records

	Number of Days		*Number of Days Between Flows*	
	Flood Days vs Flood Days with CC		**Day Since Last Flood vs Days Last Flood CC**	
River	**W - Value**	**(p value)**	**W - Value**	**(p value)**
Almond	2515.5	0.0001	6133.0	0.0017
Clyde	2122.0	< 0.0001	3522.5	0.0203
Dee	5695.5	0.0001	6391.5	0.0013
Earn	3101.5	< 0.0001	4323.5	0.0001
Findhorn	2357.5	0.0016	2132.5	0.0001
Spey	2870.0	0.0032	4466.0	0.0001

Significant at 95% confidence level

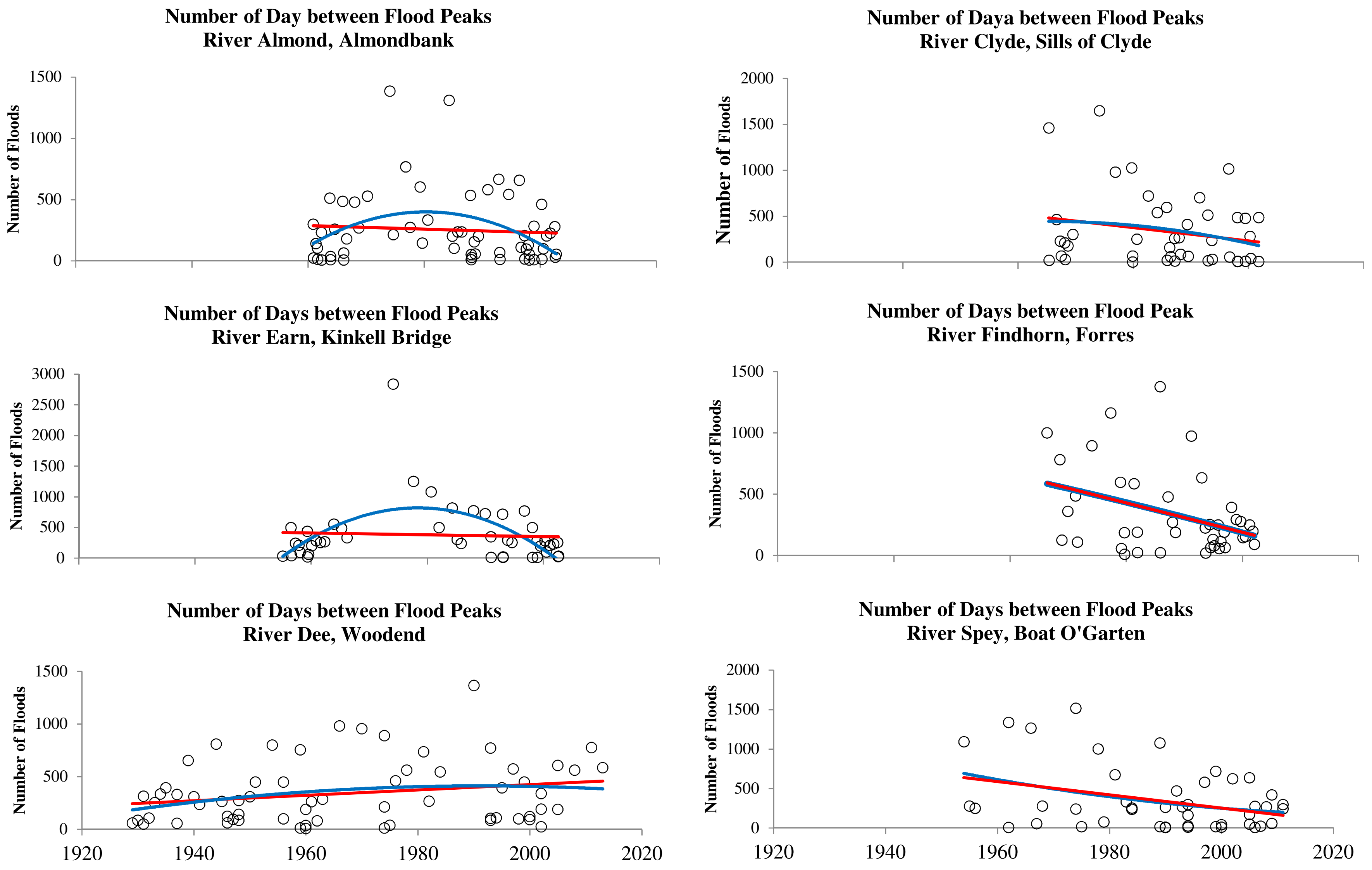


Figure 2.7: Changes in the number of days between 1:2 year flood peaks for all six catchments. The graphs include a regression line shown in red and local-weight smoothing curve (LOESS curve) shown in blue.

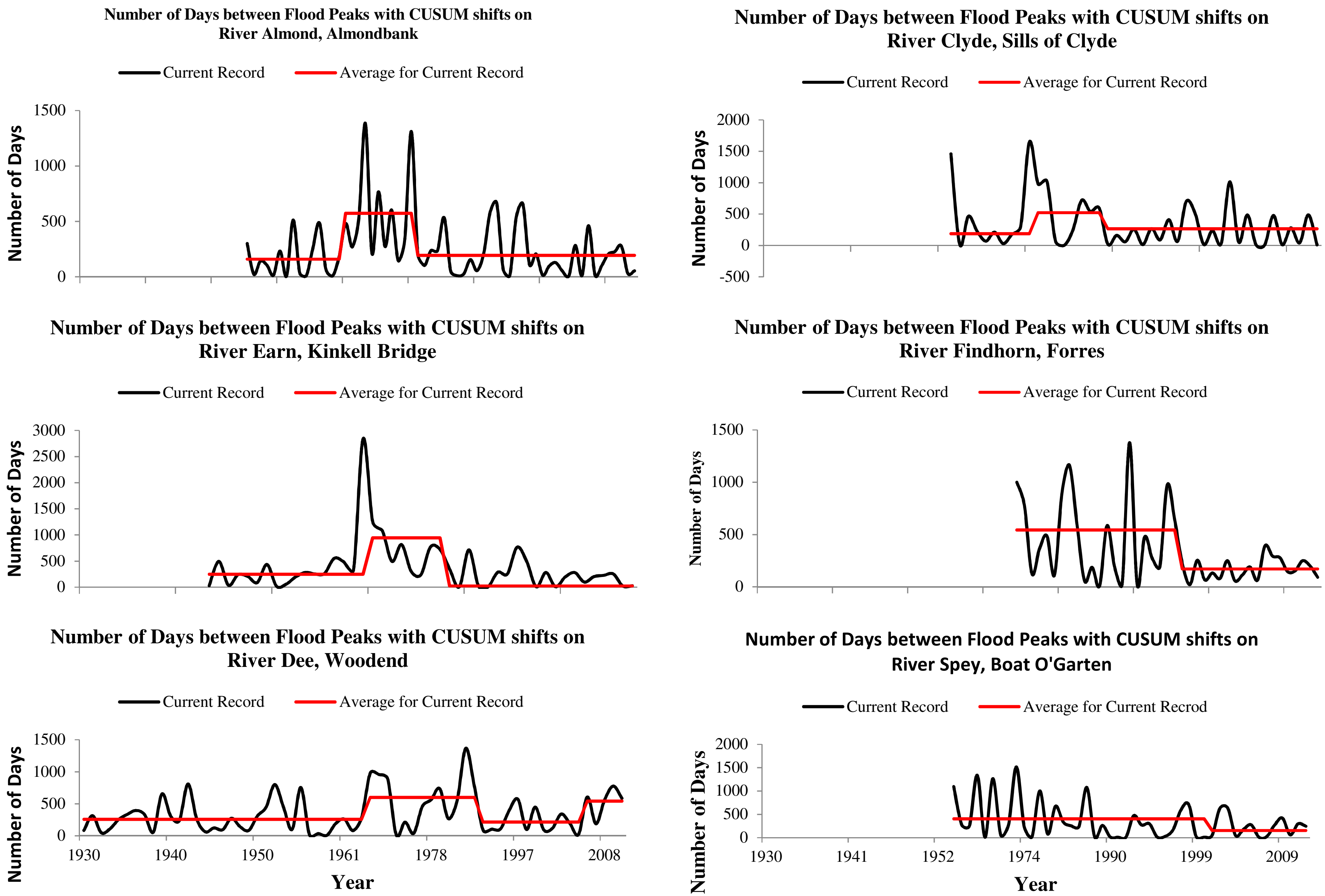


Figure 2.8: Number of days between 1:2 year flood peaks showing statistically significant shifts for all six rivers. The change in the mean number of days which occurs with each shift is shown in red.

This would suggest that with future changes in climate the frequency of 1:2 year flood flows would be much more consistent through time and thus muting previously so-called 'flood-poor' periods.

Table 2.6 Mann-Kendall Results for each River for the Number of Times 1:2 year Flow Exceeded and Number of Days between 1:2 year Flood Peaks with Climate Change

	Number of Times 1:2 year Flow Exceeded with Climate Change			*Number of Days between 1:2 year Flood Peaks with Climate Change*		
River	**Z - Value**	**Upwards Trends (p value)**	**Downwards Trend (p value)**	**Z - Value**	**Up-wards Trends (p value)**	**Downwards Trend (p value)**
Almond	0.9221	0.1782	0.8218	-0.4536	0.6749	0.3251
Clyde	2.7887	0.0026	0.9974	-1.6888	0.9544	0.0456
Dee	-0.1225	0.5487	0.4513	1.0899	0.1379	0.8621
Earn	0.0602	0.4760	0.5240	0.8031	0.2110	0.7890
Findhorn	2.8399	0.0023	0.9977	-1.8142	0.9652	0.0348
Spey	1.2691	0.1022	0.8978	-0.1793	0.5711	0.4289

Significant results shown in red. Significant at 95% confidence level

When the average number of days between 1:2 year flood peaks is investigated pre- and post- climate change a much less dramatic trend over time in average number of days per decade can be seen with climate change i.e. the 'flood-poor' periods become much more muted with a climate enhanced flow record and thus the occurrence of 1:2 year flood peaks is more consistent over time (Figure 2.10). All rivers show an overall decrease in the average number of days between 1:2 year flood peaks of between 44% and 67%, with the Clyde showing the biggest fall of 67% and the Dee showing the smallest decline at 44%. Mann U Whitney tests comparing the number of 1:2 year floods pre- and post-climate change confirmed that the effect of climate change would be significant for all

Table 2.7 CUSUM Analysis: Number of 1:2 year Flood Flows with Climate Change

		Change Point 1					*Change Point 2*				
River	**Record Length (years)**	**Start Date**	**End Date**	**Mean**	**St. Dev.**	**p-value**	**Start Date**	**End Date**	**Mean**	**St. Dev.**	**p-value**
Almond	58	1955	2012	2.73	2.604	<0.0001					
Clyde	55	1958	1989	1.59	1.266	<0.0001	1990	2010	4.10	3.064	0.00395
Dee	84	1929	2012	2.17	1.938	<0.0001					
Earn	64	1948	1956	2.79	2.891	<0.0001					
Findhorn	55	1957	1979	1.39	1.547	<0.0001	1980	2012	3.43	1.697	0.0015
Spey	60	1953	2012	3.43	3.671	<0.0001					

rivers (Table 2.5). This suggests statistically that future changes in river flows with climate change could potentially be more than would be expected due to natural variability. Mann-Kendall tests revealed there was no significant upwards trend in the any of the rivers and only a significant downwards trend in the Findhorn (Table 2.6). CUSUM analysis (Table 2.8) on each river revealed that on the Dee and the Earn that shifts and changes in the frequency of flood peaks between wetter and drier periods would no longer be present under climate change. It could therefore be argued that the flow record is 'more stationary' in nature with climate change than previously and that the occurrence of channel forming 1:2 year flows will be more consistent through-out the flow record. The Almond, Clyde and Spey all exhibit three significant periods of changing frequencies in the number of days between flood peaks, going from 'flood-rich' to 'flood-poor' and back to 'flood-rich'. However, the difference between the shifts is much smaller when compared to those found on the current record. For example, on the Almond the shifts occur at around the same time but the mean number of days for each period goes from 159, 573, 194 days to 79, 224, 101 days. A similar pattern is seen in the Clyde where the average number of days shifts from 187, 647, 228 days to 132, 340, 121 days. The Spey goes from having only one significant shift pre- climate change to having three with an enhanced climate change record with a distinct 'flood-rich', 'flood-poor', 'flood-rich' pattern with mean values for the number of days between floods of 118, 232 and 96. In the Findhorn the CUSUM mirrors the Mann-Kendall tests and non-climate change CUSUM for the current flow record where by the one shift that occurs is a decrease in the number of days between flood peaks suggesting an increasing occurrence of food peaks. In the climate enhanced records the shift in the mean number of days between 1:2 year flood peaks is less evident.

Table 2.8 CUSUM Analysis Number of Days between 1:2 year Flood Peaks with Climate Change

		Change Point 1					*Change Point 2*					*Change Point 3*				
River	Record Length (years)	Start Year	End Year	Mean	St. Dev.	p-value	Start Year	End Year	Mean	St. Dev.	p-value	Start Date	End Date	Mean	St. Dev.	p-value
Almond	58	1955	1963	79.2	112.86	<0.0001	1963	1988	224.0	202.75	0.0022	1988	2012	100.83	106.947	0.0175
Clyde	55	1960	1968	132.0	122.10	<0.0001	1969	1979	340.7	308.18	0.3714	1979	2012	121.90	117.511	0.0149
Dee	84	1929	2013	209.8	219.60	<0.0001										
Earn	64	1948	2010	156.7	177.06	<0.0001										
Findhorn	55	1961	1998	226.8	229.19	<0.0001	1999	2012	96.4	67.75	0.0071					
Spey	60	1953	1970	118.4	121.19	<0.0001	1971	1999	232.1	211.76	0.0167	1999	2010	96.83	88.172	0.0190

Table 2.11 CUSUM Analysis: Number of Days between Bedload Moblisations

		Change Point 1					*Change Point 2*					*Change Point 3*					*Change Point 4*				
River	Record Length (years)	Start Year	End Year	Mean	St. Dev.	p-value	Start Year	End Year	Mean	St. Dev.	p-value	Start Year	End Year	Mean	St. Dev.	p-value	Start Year	End Year	Mean	St. Dev.	p-value
Almond	58	1955	1962	32.78	41.44	<0.0001	1962	2012	50.65	55.36	0.0051										
Clyde	55	1957	1977	58.41	63.36	<0.0001	1977	2012	43.25	48.79	0.0426										
Dee	84	1929	1934	57.00	67.34	<0.0001	1934	1974	135.11	146.56	0.0016	1974	1993	298.17	201.85	0.0186	1993	2012	88.78	81.30	0.0043
Earn	64	1948	1957	136.58	124.05	<0.0001	1960	1989	479.08	472.08	0.0021	1990	2010	183.16	184.37	0.0034					
Findhorn	55	1959	2013	45.37	128.23	<0.0001															
Spey	60	1953	1992	118.35	121.19	<0.0001	1993	2010	234.12	224.36	0.0319										

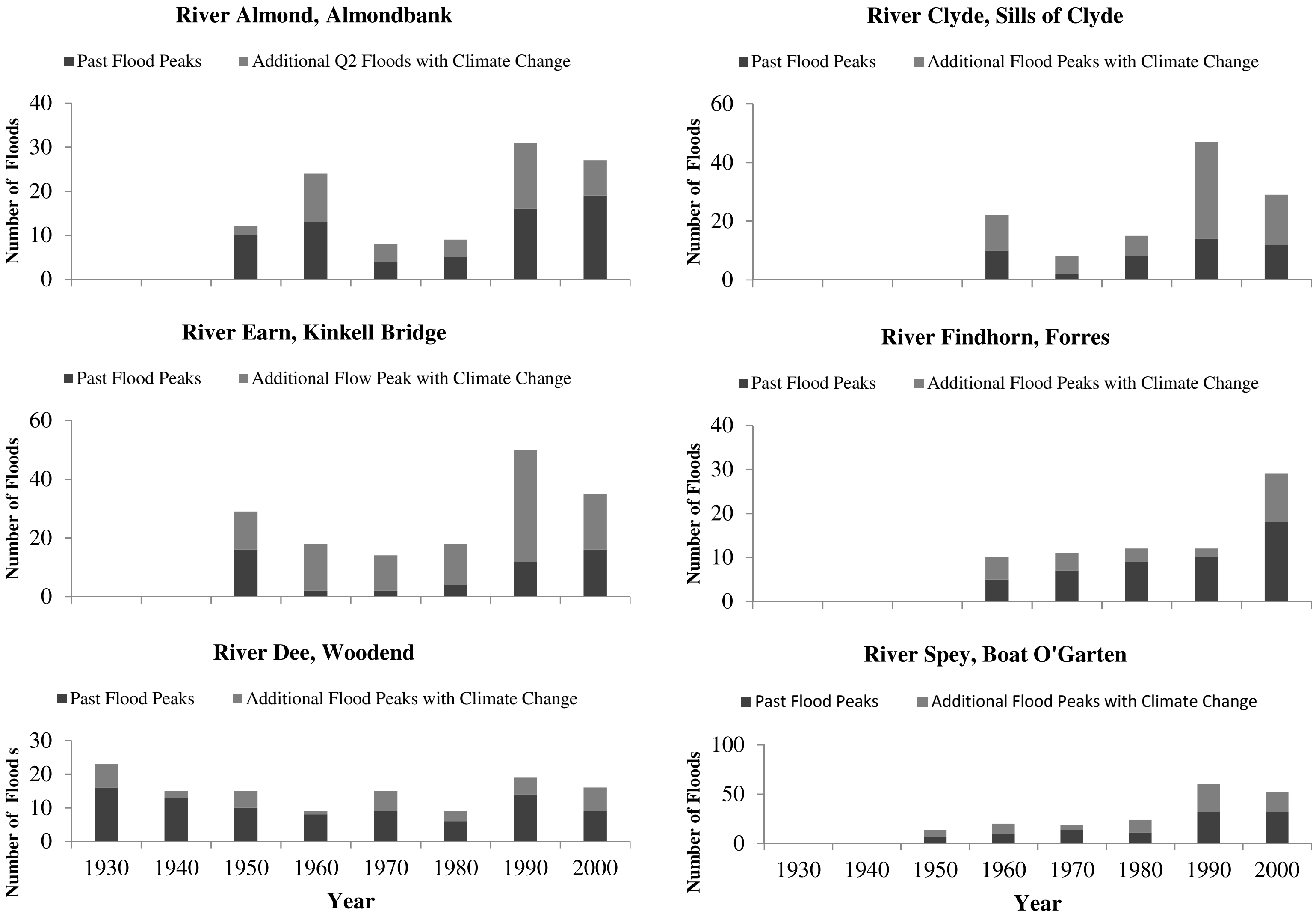


Figure 2.7: Changes in the number of 1:2 year flood flows per decade under a climate change enhanced flow record for all six catchments.

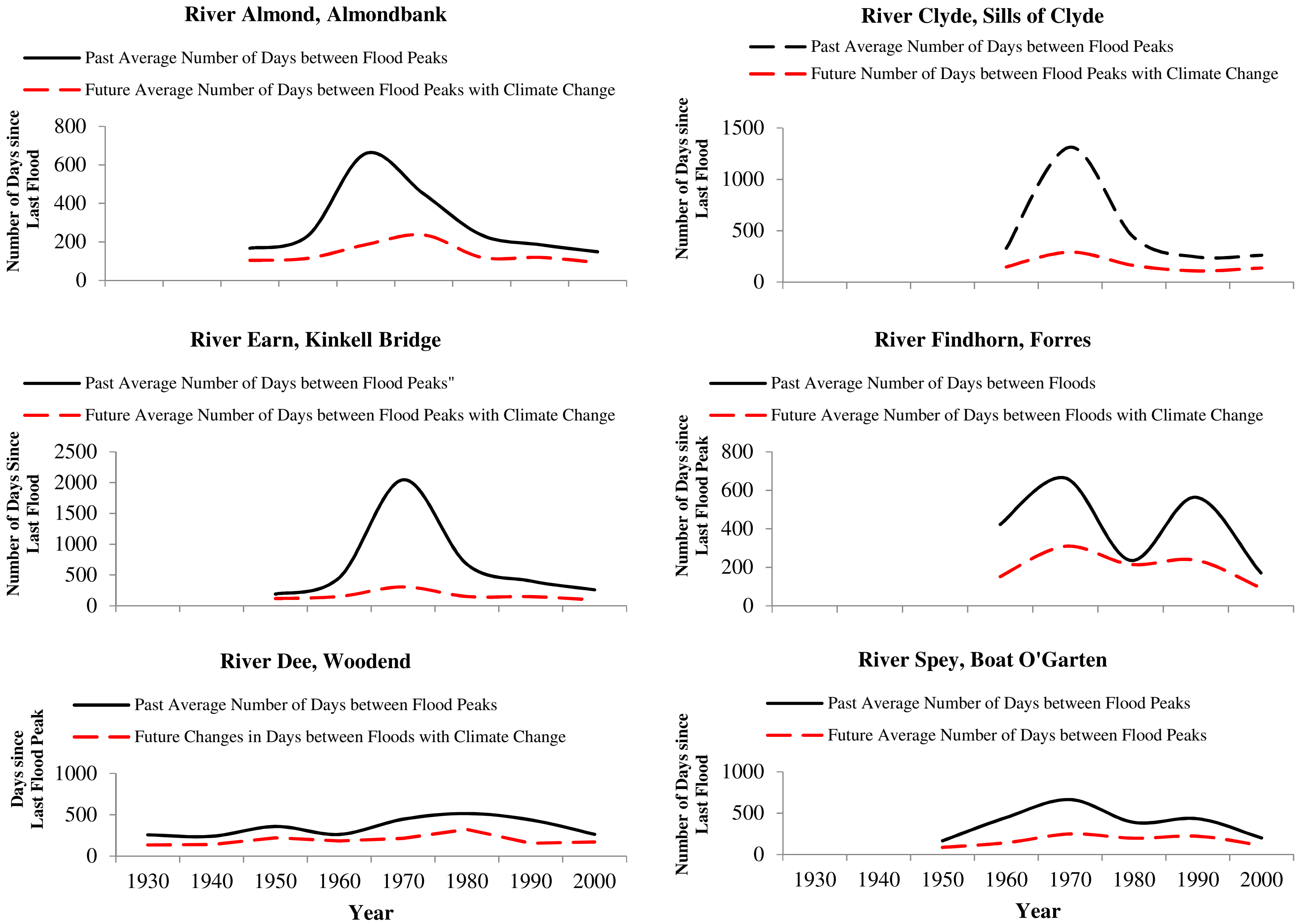


Figure 2.10: Change in the average number of days between 1:2 year peak flows per decade between the current flow records and a climate change enhanced flow record.

2.3.3 Trends and Step Changes in Bedload Activity

With an increasing and decreasing frequency of flood flows the geomorphic activity of the river will vary over time, coined above as 'geomorphically-active' periods and 'geomorphically-inactive' periods. To explore these phenomena further and specifically in relation to bedload activity the number of days between the movement of a pebble of certain size and the number of times a pebble of certain size moved was investigated. As discussed above a pebble size of 63 mm was used for all rivers except the Spey where a 22 mm pebble was used. As the main aim of the study was to look at patterns in the movement of bedload, the sensitivity of the results to the 'D_{50}' selected was considered. If the pebble selected was too small then any patterns in bedload transport may not be exposed as the pebble would move too frequently. Conversely if the pebble size selected was too large then only the extreme events would be exposed as the pebble would not have moved frequently enough for any trends or patterns in the data to be uncovered.

When the frequency of a 63 mm pebble was examined for each river (Table 2.9) it was found to provide the best overall movement frequency for all rivers. If a larger pebble (90 mm) had been used for Clyde, Dee and Earn then movement frequency would have potentially been too low at averaging 0.5 times a year.

Table 2.9 Frequency of Pebble Movements since Flow Records Began

	Current Flow Record						*Climate Change Enhanced Flow Record*					
Pebble Size (mm)	**Almond (1955)**	**Clyde (1957)**	**Dee (1929)**	**Earn (1948)**	**Findhorn (1958)**	**Spey (1951)**	**Almond (1955)**	**Clyde (1957)**	**Dee (1929)**	**Earn (1948)**	**Findhorn (1958)**	**Spey (1951)**
16	210.82	190.35	218.88	185.70	191.48	10.51	220.28	203.87	253.16	200.09	208.09	15.67
22	139.91	115.69	121.11	110.97	143.65	1.61	152.23	130.18	151.32	130.28	171.69	3.11
32	73.46	50.25	49.56	44.70	73.78	0.11	83.72	63.33	24.39	59.61	96.70	0.23
45	31.89	18.67	15.59	11.88	34.48	0.02	40.09	26.98	23.41	19.86	51.07	0.02
63	12.33	4.80	4.12	1.80	12.17	0	17.42	8.49	6.34	4.45	17.56	0
90	2.91	0.58	0.61	0.11	2.91	0	4.32	1.56	1.33	0.38	4.87	0
128	0.54	0.04	0.04	0	0.59	0	0.96	0.13	0.09	0.03	1.00	0

Pebble size selected for each river highlighted in yellow. The starting year of each flow record is shown in brackets.

If a smaller pebble (45 mm) had been selected movement frequency on the Almond and Findhorn would have potentially been too high averaging at 33.2 time per year. Although it could be argued that a pebble size of 90 mm with a movement frequency of 2.91 for the Almond and Findhorn was within the same range as 63mm pebble on the Clyde, Dee and Earn, it was decided to still use a 63mm pebble to ensure consistency in relation to the geomorphic effect of the initiation of movement for a pebble of that size. In the Spey the frequency at which 22mm pebble moved (3.11 times per year) which was within the range (1.8 to 4.8 times per year) for the frequency of movement for a 63 mm pebble on the Clyde, Dee and Earn and therefore was considered an appropriate figure.

Mann-Kendall tests revealed that there was not a significant downwards trend in the number of days between modelled bedload movements for any river, which mirrors the results found when analysing the hydrological record. Only the Spey showed a significant upwards trend in the number of days between bedload movements with a p value of 0.0103. All the results are shown in Table 2.10. CUSUM analysis (Table 2.11, pg. 39) revealed one statistically significant shift in the number of days between bedload movement in the River Almond, Clyde and Spey.

Table 2.10 Mann-Kendall Results for each River for Bedload Mobilisation

	Number of Times Bedload Mobilised			***Number of Days between Bedload Mobilisation***		
River	**Z - Value**	**Upwards Trends (p value)**	**Downwards Trend (p value)**	**Z - Value**	**Up-wards Trends (p value)**	**Downwards Trend (p value)**
Almond	1.5538	0.0601	0.9399	0.4660	0.3206	0.6794
Clyde	4.0748	0.0000	1.0000	-0.2528	0.5998	0.4002
Dee	0.1130	0.4550	0.5450	1.4160	0.0784	0.9216
Earn	1.0496	0.1470	0.8530	-0.1461	0.5581	0.4419
Findhorn	0.7082	0.2394	0.7606	-3.5834	0.9998	0.0002
Spey	1.2872	0.0990	0.9010	2.3163	0.0103	0.9897

Significant results shown in red. Significant at 95% confidence level

Table 2.13 Mann-Kendall Results for each River for Bedload Mobilisation with Climate Change

	Number of Times Bedload Mobilised with Climate Change			*Number of Days between Bedload Mobilisation with Climate Change*		
River	**Z - Value**	**Upwards Trends (p value)**	**Downwards Trend (p value)**	**Z - Value**	**Up-wards Trends (p value)**	**Downwards Trend (p value)**
Almond	1.9487	0.0257	0.9743	-1.0380	0.8504	0.1496
Clyde	3.9472	0.0000	1.0000	0.4617	0.3222	0.6778
Dee	0.8613	0.1945	0.8055	0.7282	0.2332	0.7668
Earn	0.5496	0.2913	0.7087	0.4560	0.3242	0.6758
Findhorn	2.4207	0.0077	0.9923	-2.5263	0.9942	0.0058
Spey	0.7669	0.2216	0.7784	-0.1209	0.5481	0.4519

Significant results shown in red. Significant at 95% confidence level

The Almond and Spey showed a shift towards a decrease in the activity of the river occurring in 1962 and 1992, in which the number of days between bedload movements increased from 34 to 50 and 118 to 234 respectively. In the Almond the shift towards a decrease in the bedload activity around 1963 is roughly the same time that there was a significant shift towards a decrease in the number of days between flood peaks. However, the shift in the hydrological record back to a decrease in the number of days between floods is not present in the bedload record. Possibly because flows lower than 1:2 years are required to move a 63 mm pebble at that point of the Almond. The more westerly Clyde showed the opposite trend in that there was significant increase in the number of bed activity in around 1977 where the mean number of days between floods decreased from 58 to 43. The Earn showed two significant shifts going through a 'more-active' to 'less-active' to 'more-active' period. The first shift occurring in 1957, around 5 years before the shift towards a greater number of days between flood peaks occurred in the River Almond. The second shift returning to decreased number of days between floods occurring in 1990 corresponds with timing suggested for increase flood activity in Scotland (Black and Burns, 2002). In the Dee four significant shifts were found, with the first three shifts showing an increase in the mean number days between floods from 57 to 135 to 298 before dropping in around 1993 to a mean number of 88 days between bedload movements. No statistically significant shifts in the number of days between bedload activity was found in the River Findhorn.

CUSUM (Table 2.12 pg. 46) and Mann-Kendall (Table 2.13) analysis on the enhanced climate change record for the Almond, Clyde, Earn and Spey all showed no significant upwards or downwards trends and no significant shifts in the number of days between flood peaks. The Findhorn showed a significant downwards trend in the number of days between bedload movements, which is mirrored in the flow record where the same decrease in the number of days between flood peaks is present. In the Dee two significant shifts were identified: a short 10 year period, a longer 55 year period followed by a shorter 20 year period. The mean number of days between bedload movements was found to be 46, 100 and 60. Mann-U Whitney tests confirmed that there was a significant difference in the number of days between bedload movements between the current record and an enhanced climate change record for all rivers except the Almond and Spey (Table 2.14). As the number days that bedload is mobilised is found not to be statistically different pre- and post- climate change, it suggests that the number of days that bedload is moving either side of the flood peak has increased, but there has not been a statistically significant increase in the number of flood peaks. Additionally, it could suggest that the Almond and Spey may potentially be more resilient to future changes in bedload activity compared to the other rivers investigated here; however more detailed bedload modelling would be required to confirm this. Figure 2.11 shows the difference in the shifts and mean number of days between flood peaks pre- and post- climate change.

All rivers showed no significant upwards or downwards trend in the number of active bedload days (Table 2.10), and only the Almond, Clyde and Earn showed significant shifts (Table 2.15) in the number of days bedload was active.

Table 2.12 CUSUM Analysis: Number of Days between Bedload Mobilisations with Climate Change

		Change Point 1					*Change Point 2*					*Change Point 3*				
River	Record Length (years)	Start Year	End Year	Mean	St. Dev.	p-value	Start Year	End Year	Mean	St. Dev.	p-value	Start Year	End Year	Mean	St. Dev.	p-value
Almond	58	1955	2012	45.54	49.00	<0.0001										
Clyde	55	1957	2012	70.77	96.19	<0.0001										
Dee	84	1929	1937	46.48	50.86	<0.0001	1937	1992	100.1	100.41	0.0029	1993	2013	60.54	57.36	0.0075
Earn	64	1948	2010	137.2	157.39	<0.0001										
Findhorn	55	1958	1977	126.7	125.64	<0.0001										
Spey	60	1953	2010	152.6	164.07	<0.0001	1978	2010	71.86	74.69	0.0304					

The Almond and Clyde both showed one statistically significant shift in the number of bedload events (Table 2.15). In the Clyde and Almond there was an increase in bedload activity in 1989 and 2004 with the mean number of days bedload was active per year going from 3.22 to 6.9 and 11.5 and 17.8 respectively. Two shifts were identified in the Earn in 1963 and 1989 where the mean number of bedload active days went from 2.4 down to 0.5 and then back up to 2.7 suggesting the presence of periods of increased bedload activity and decreased bedload activity. For a climate enhanced flow record only the Findhorn, Clyde and Dee showed significant trends within their record. The Findhorn and Clyde both showed a significant upwards trend in the number of days (Table 2.13) that bedload was active. The Clyde showed a significant shift in 1983 in which number of days bedload was active annually increased from 5 to 11 (Table 2.16). CUSUM

Table 2.14 Mann U Whitney Test Results showing the Significant difference between Past Flow Records and Climate Change Enhanced Flow Records

	Number of Days		*Number of Days Between Flows*	
	Active Bedload Days vs Active Bedload Days with CC		Days Since Bedload Last Active vs Days Since Bedload last Active with CC	
River	W - Value	(p value)	W - Value	(p value)
Almond	2,789.00	0.0008	116,454.00	0.0720
Clyde	2,259.00	0.0001	35,034.50	0.0169
Dee	8,726.50	< 0.0001	49,686.50	0.0145
Earn	3,146.50	< 0.0001	7,274.50	0.0060
Findhorn	1,712.50	< 0.0001	20,088.50	< 0.0001
Spey	2,811.00	0.0011	5,893.50	0.5245

Non-significant results shown in red. Significant at 95% confidence level

analysis (Table 2.16) revealed the Dee had one shift in which the mean number of flood days increased from 5.6 to 8.5 days, which occurred around 1994. Mann-U Whitney tests confirmed that there was a significant difference in the number of days bedload was active between the current record and an enhance climate change record for all rivers (Table 2.14).

Table 2.15 CUSUM Analysis: Number of Time Bedload has been Mobilised

		Change Point 1					*Change Point 2*					*Change Point 3*				
River	**Record Length (years)**	**Start Year**	**End Year**	**Mean**	**St. Dev.**	**p-value**	**Start Year**	**End Year**	**Mean**	**St. Dev.**	**p-value**	**Start Date**	**End Date**	**Mean**	**St. Dev.**	**p-value**
Almond	58	1955	2004	11.52	5.59	<0.0001	1997	2012	17.88	5.28	0.0077					
Clyde	55	1957	1989	14.64	7.54	<0.0001	1990	2012	25.78	11.06	0.0001					
Dee	84	1929	2010	3.90	3.23	<0.0001										
Earn	64	1948	1963	2.375	2.28	<0.0001	1964	1989	0.54	0.81	0.0031	1990	2010	2.76	2.343	0.0055
Findhorn	55	1957	2012	1.245	1.07	<0.0001										
Spey	60	1953	2010	1.621	1.75	<0.0001										

The statistically significant shifts present in the current record for the Almond and Earn are no longer present under a climate enhanced flow records. This suggests that potentially the number of days bedload is active on these rivers will be more consistent year on year in the future and any dip in the bedload activity will be much more muted than previously.

Table 2.16 CUSUM Analysis: Number of Times Bedload was Mobilised under Climate Change Enhanced Flow Record

		Change Point 1					*Change Point 2*				
River	**Record Length (years)**	**Start Year**	**End Year**	**Mean**	**St. Dev.**	**p-value**	**Start Year**	**End Year**	**Mean**	**St. Dev.**	**p-value**
Almond	58	1955	2012	16.95	7.774051	<0.0001					
Clyde	55	1957	1982	5.24	9.499875	<0.0001	1983	2012	11.58	12.39158	<0.0001
Dee	84	1929	1993	5.6	4.15	<0.0001	1994	2010	8.5	4	0.0245
Earn	64	1948	2010	4.43	4.02	<0.0001					
Findhorn	55	1958	2013	8.25	3.00331	<0.0001					
Spey	60	1953	2010	3.17	2.6828	<0.0001					

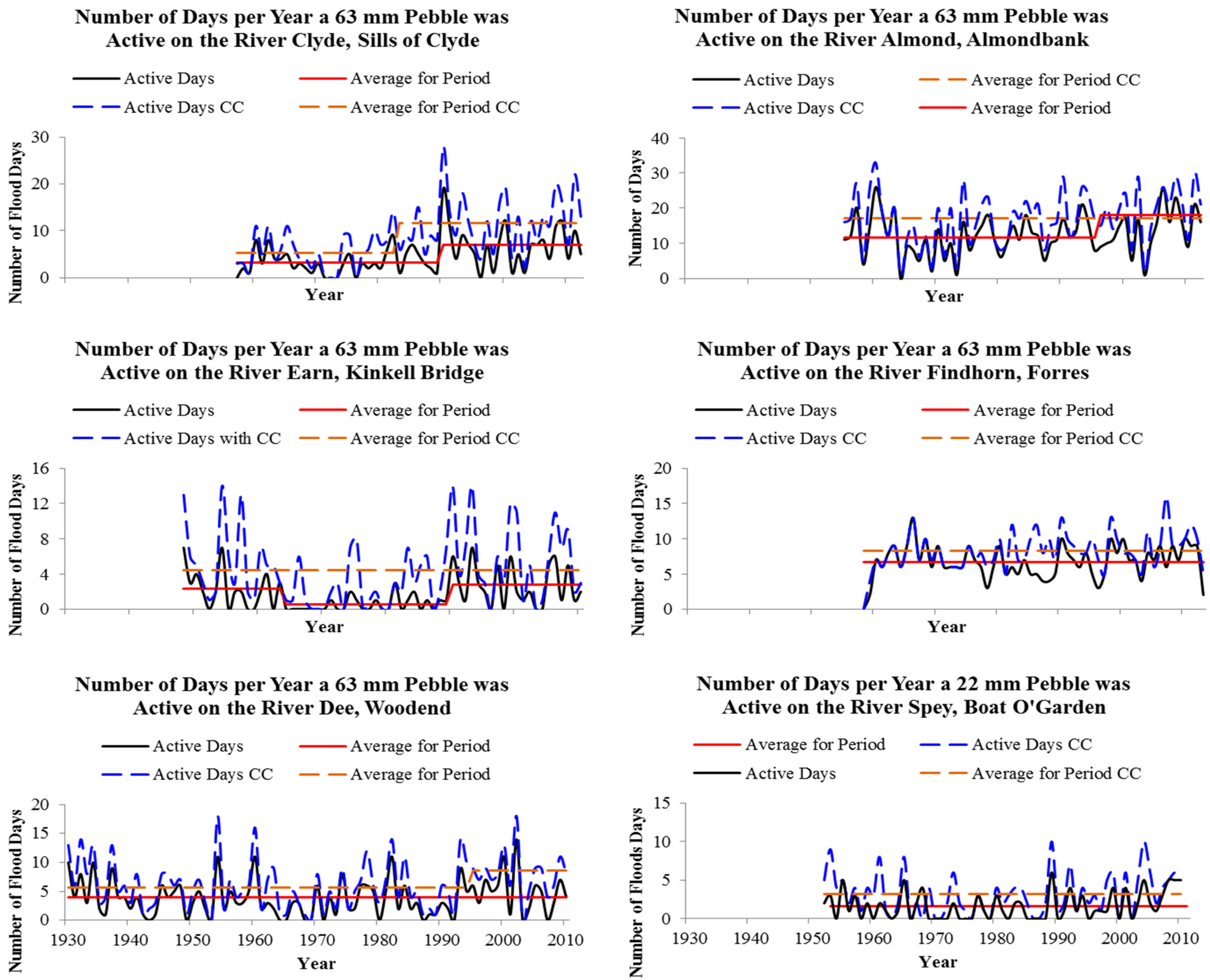


Figure 2.11: Change in the average number of days bedload was mobilised for all six catchments pre and post a climate change enhanced record. The change in the average number of active days is also shown

2.4 DISCUSSION

2.4.1 Current Patterns and Trends

The analysis undertaken here illustrates that there have been statistically significant shifts in the frequency of geomorphologically significant floods within Scottish rivers. However the number of shifts and the timing of these shifts vary between rivers. Potentially this is due spatial differences in local weather patterns, catchment size, and land management practices and possibly to some extent record length (Robson et al., 1998; Robson, 2002). Similar trends found previously have suggested that Scotland has gone through ‘flood-poor’ and ‘flood-rich’ periods, i.e. times of increased flood activity and decreased flood activity based on changes in the precipitation record (Black and Burns, 2002; Afzal et al., 2011). The 1970s are often highlighted as being a drier ‘flood-poor’ period before entering a ‘flood-rich’ period in the late 1980’s which was marked by extreme winter flooding across Scotland (Hulme and Jenkins, 1998; Werritty and Leys, 2001). The most notable being the 1990 and 1993 floods on the River Tay (Black and Anderson, 1994) and large floods on the River Clyde in 1985 and 1994 (Black and Bennett 1995; JBA Consulting, 2005). Here, when examining trends and shifts in potentially geomorphologically significant flows across six Scottish rivers a shift towards more frequent flooding (reduced number of days between flood events) occurred in 1990 on the Clyde and Almond, with the Dee in the north-east following suit slightly later in 1993. In the more northerly rivers of the Spey and Findhorn this trend is not seen until 2000, 10 years after the shift occurred in the Clyde and Almond. The Earn situated in the central-belt of Scotland also showed a shift towards increased flood frequency in 1997 meaning a seven year lag when compared to the more southern Clyde and Almond. The reason for these shifts in flood frequency, which have also been seen in flood and precipitation records throughout Europe (Schmocker-Fackel and Nae, 2010; Villarin et al., 2011; Hannaford et al., 2013) and the rest of the UK (Pattison and Lane, 2011; Wilby and Quinn, 2013), has been increasingly discussed in the literature over the last few decades (Wilby et al., 1997; Fowler and Kilsby, 2002; Schmocker-Fackel and Nae, 2010; Lavers et al., 2011; Pattison and Lane, 2011; Wilby and Quinn, 2013; Foulds et al., 2014). These patterns can be linked to changes in the dominance of the different atmospheric circulation systems that affect the UK (Lamb, 1972; Latif and Barnett, 1994; Hurrell, 1996; Robson, 1998; Ambaum et al., 2001; Knight et al., 2006; Lavers et al., 2011). However, a number of studies (Wilby et al., 1997; Briggs and Atkinson, 2011; Burt and Hawden, 2013) have suggested that shifts like those found here can potentially be linked to the strength of different phases of the North Atlantic Oscillation (NAO). The NAO is climatic phenomena which controls the strength of westerly winds across Europe based on the atmospheric pressure at sea level between the Icelandic low and Azores high. Years when there is a strong positive NAO (large difference in pressure between the Icelandic low and Azores high) the UK experiences much milder, wetter winters (Hurrell et al., 1996; Hurrell et al., 2003). When Pattison and Lane (2011) investigated what Lamb weather types were driving extreme floods back to 1770 for the Eden catchment in north-west England, three distinct 'flood-rich' periods were identified in 1873 to 1904, 1923 to 1933 and 1994 to present. These events again appeared to correlate with a strong positive NAO bringing mild wet weather to the UK. However, when Wilby and Quinn (2013) used an objective weather classification scheme to reconstruct the potential atmospheric drivers for the occurrence of floods across the UK 'flood-rich' periods were found to occur between 1908 to 1934, 1977 to 1988 and 1998 onwards. Despite the slight differences in the timings between 'flood-poor' and 'flood-rich' periods these two studies support the results from this study confirming that the frequency of floods is not stationary in nature and at present the UK in general is experiencing a period of increased winter wetness and thus high winter flows. The River Dee post-2004, unlike the other rivers, shows a slight shift back to decreasing occurrence of geomorphic flows in 2004. This change could be linked to high-profile droughts that effected the east of Scotland and the UK as a whole between 2004 and 2006 and then later between 2010 and 2012 (Marsh et al., 2007; Marsh, 2004; 2012; Kendon et al., 2013; Hannaford, 2015). The Findhorn and Spey both showed a shift towards an increase in the occurrence of floods in 2000. This potentially suggests that despite shorter records potentially being 'wired' to show an increase in high flows since the 1960's due to an increased prevalence of a positive NAO (Robson, 2002 and Wilby and Quinn 2013), there has been an intensification of this trend in these rivers in 2000 either due to climate change or human modification within the catchment.

No significant shifts suggesting 'flood-poor' or 'floor-rich' periods appeared when the number of flood days per year was investigated. Potentially this is because the 1:2 year flow threshold selected was too high for the difference in the number of floods days annually to be significant. Often the difference between wetter years and drier years was only two floods, meaning that the CUSUM value would oscillate around the median value with no significant turning points in data marked by an upwards or downwards trend. The Mann-Kendall tests did reveal a significant upwards trend in the number of 1:2 year flood flows with in the Findhorn, Clyde and Spey catchments. The flow records for these rivers all started around the middle to late 1950's (1957, 1958, and 1953 respectively) which correlates with an increased prevalence of a more positive NAO bringing milder condition across the UK as a whole and wetter conditions to Scotland since the 1960's (Wilby et al., 1997; Hannaford and Marsh, 2008). Hannaford and Marsh's (2008) study, which looked at trends in high-flows in undisturbed catchments across the UK found that in western upland catchments there was a significant upwards trend in the occurrence of high flows which correlated with the recent increased prevalence of positive North Atlantic Oscillation Index (NAOI). Similar results were also found to have occurred in a 30 year record in the uplands of the Severn catchment in Wales (Biggs and Atkinson, 2011). In addition, to the shift towards a more positive NAO, an increasing number of Atmospheric Rivers (narrow bands of concentrated water vapour transported from the subtropics to mid-latitudes) have also been suggested as a potential driver for increased winter flooding in the UK (Lavers et al., 2011; Hannaford, 2015). It had been found that since 1970, the 10 largest floods in the UK have coincided with Atmospheric Rivers (AR), and years where ARs are not present, winter flooding has been at its lowest, highlighting their importance in the UK's flood record (Lavers et al. 2011). The results from these studies highlight the importance of record length when looking for trends and shifts in the high flows. As several studies have shown (Robson, 2002; Murphy et al., 2013; Wilby and Quinn, 2013), shorter records of less than 50 years are 'hard wired' to show an upward trend in the number of flood days because they start during the relatively 'drought-rich' period of 1970 (Hannafords, 2015) and end in a time of increased winter rainfall due to an increasing shift towards positive NAO. Although all the records used here are greater than 50 years in length to reduce the risk of natural variability in river flows being portrayed as significant trends, these three catchments are the most westerly catchments surveyed with flow records beginning just prior to 1960 when a trend towards increased winter wetness is suggested to have occurred. This may explain why we see this upwards in the Findhorn, Spey and Clyde and not in the longer records of the Dee and Earn which start at least 10 years prior to 1960 and the Almond which lies much further east in the rain shadow.

It is recognised that the shifts and trends identified here may not be completely attributed to changes in rainfall as land management practices may also considerably alter the flow regime of a river; and thus there is a human element which needs to be considered when investigating the reason for changes in flood frequency. Over the last 60 years human activity has had marked impact on rivers and their surrounding catchment through urbanisation, afforestation, deforestation, field drainage, agricultural intensification, channel modifications and water resources management such as abstraction (Wheater, 2006; Wheater and Evans, 2009). Scotland in general since between 1940 and 1990 has seen an increase in built land (36%) arable land (11%) and forestry plantations (613%) and decrease in grassland (10%) and blanket-mire and heather moorland (23%) (Mackey et al., 1998). Since the post-war introduction of the 1947 Agriculture Act to ensure sustainable food production in the UK, the increase in arable land has been accompanied by considerable intensification of agricultural practices, improved field drainage and extensive removal of hedgerows (Robinson, 1990; O'Connell et al., 2007; Wheater and Evans, 2009). These changes have lead in many catchments to increased soil compaction and erosion, reduced soil infiltration and storage and thus increased overland flow (Heathwaite et al, 1990; Burt, 2001; Wheater, 2006; O'Connell, 2007). In Scotland, the eastern and central lowland catchments of the Dee, Earn and Almond which are located within arable rich areas saw the greatest increase in hedgerow removal between 1940 and 1990 (around 1 km per km^2 area) with around a 50 % decrease between 1940 and 1970 (Mackey et al., 1998). During this period the Dee, Earn and Almond all experienced a decreased period of flood frequency and thus the reported increase in arable farming and hedgerow removal is unlikely to have on its own caused an abrupt shift in flood frequency. It is also unlikely that increasing field drainage is likely to have had a marked effect on flood flow as land drainage during this time is mainly associated with re-draining the land rather than establishing a new drainage patterns (Robson, 1990). Although the Spey and Findhorn saw the biggest increase in arable land of the catchments investigated here, the removal of hedgerows is more muted (around 0.25 km per km^2 area) and within both catchments arable land only accounts of 0.4 % of the land cover. Therefore, the effect on flood frequently would be expected to be small. The Clyde area saw a marked decrease in arable land of between 4 and 6 % between 1940 into improved pasture; however, during this period built infrastructure has increased by up to 2.5 %, much more than any of the other catchments studied here (Mackey et al., 1998). The increase in built infrastructure in the western catchments such as the Clyde and central lowland catchment of the Almond (2% increase) may explain why the shift towards an increased flood frequency occurred in 1990's, however there was a 10 year lag before the same trend was seen in the Spey and Findhorn, where the increase in built infrastructure was much less (1%) and only accounts for 0.1% and > 0.1% respectively of catchment land use (Mackey et al., 1998). The Spey dam which was constructed just prior to the start of the flow record may also potentially mute to a small extent the flood behaviour of the river and explain the lag time in the step-change in flood frequency. Traditionally in natural UK catchments flooding occurs following prolonged periods of rainfall and wet antecedent conditions, in urbanised areas where infiltration is low the catchment is unable to absorb even small volumes of precipitation, meaning increased overland flow resulting in high flows potentially occurring more frequently (Wheater, 2006). Consequently, the more urbanised Clyde and Almond would be expected to be more sensitive to changes in rainfall than more the more rural catchments.

Afforestation in Scotland has significantly increased between 1940 and 1990 by over 600% (Mackey et al, 1998). This has primarily been through coniferous plantations which have grown rapidly from 2% of total land cover in Scotland in the 1940's to 12% in the 1990's, compared to small decreases in broadleaf woodland. Across all catchments studied here there has been a 5 to 10% increase in coniferous plantations, no change in coniferous woodland and around 1% decrease in broadleaf woodland (Mackey et al., 1998). Afforestation via coniferous plantation on upland moorland and blanket mires would in the short-term be expected to increase run-off due to soil disturbance and increased upland drainage while planting, but in the medium to longer term, once established, decrease flood flows due to higher interception and evapotranspiration rates (Johnson, 1998; Gilvear et al., 2002). When run-off between arable land and forested land were compared in a catchment in West Germany run-off was reduced by 40 % and low flows were reduced by 60% (Robinson, 1990). Similar results have been reported for the Balquhidder catchment in Scotland where conifer afforestation decreased summer flows (Johnson and Simpson, 1991). When the steady increase in coniferous plantations is considered here alongside changes in flood frequency, it is generally found that introduction of the plantation coincides with wetter periods with higher flood frequency and decreases around the 1970's when potentially the plantations have stabilised. However, a more detailed catchment by catchment analysis looking at specific introduction of plantations and run-off patterns would need to be investigated before any link between afforestation and shifts and trends in flood frequency could be confirmed. Although changes in land use and cover will undoubtedly influence flood frequency in all catchments, often the effect will be more marked on the flood magnitude rather than frequency, as often the biggest difference in land use is in the catchments ability to reduce run-off and flood peaks caused by climate variability. This theory is similar to Knox's (2000) evaluation of changing flood frequency on the upper Mississippi, where he concluded that changes in land use influenced the magnitude of smaller high frequency floods, but changes in the patterns of larger floods was defined by climatic variability. Macklin and Lewin (2003) came to a similar conclusion when looking at Holocene climate change where by it was found that land use was found to either moderate or amplify the climatic signal.

Whilst the reason for the trends are not completely understood they do highlight that rivers do not always display stationary behaviour and significant shifts in their behaviour do occur even within a human time scale. This highlights that farmers, who work the nearby floodplains, and river managers, who modify the rivers to reduce flood risk or restore them to improve their ecological status, need to understand that river behaviour is changeable and thus their management practices must be adaptable to these potential changes.

2.4.2 Pattern and Trends in a Climate Enhanced Flow Record

Changes in climate are well known to be a significant driver in channel change as climate governs a rivers flow regime. Land use and land cover are also important drivers in channel change. Consequently, any changes in current high flow trends and patterns could potentially over time have a marked effect on river morphology (Knighton, 1998; Coulthard et al., 2000; Raven et al., 2010). When a climate enhanced record is investigated the results vary from a simple enhancement of the current trends, a removal of trends and shifts completely, suggesting a move towards a more stationary regime with more consistent flooding over time, to the appearance of a more marked 'flood-rich', 'flood-poor' cycle. When the number of days between floods is considered the Almond and Findhorn showed only an enhancement of the pre-climate change flow records with mean number of day between floods for each period halving (Table 2.4 and 2.8). When 'flood-poor' periods under a climate enhanced flow record are compared to 'flood-rich' periods during the current flow record, the difference in the number of day between flood peaks is less than 65 days suggesting that what is currently considered a wet decade could become considered a dry decade. In the Clyde the drier 'flood-poor' period is about 10 years longer on the climate enhance record, however the overall mean number of days between floods is just less than half that of the current flow record. When this is considered in relation to the geomorphic activity of the river this would suggest a doubling of sediment activity during both 'flood-rich' and 'poor' periods. Significant shifts between drier and wetter periods in both the Earn and the Dee have been ironed out with the average number of days between floods for the whole record being less than previous flood-rich periods. The Spey, which previously had just one shift in 2000 toward a decrease in the number of days between floods (Table 2.8), now under a climate enhanced flow records show statistically significant shifts between 'flood-rich' and 'flood-poor' periods.

The occurrence of 1:2 year floods under an enhanced climate record shows no significant shifts in the Almond, Dee, Earn and Spey. The mean number of floods for each catchment has almost doubled in the Almond, Dee and Spey. The increase in the Earn is more modest at 0.79 floods days annually. Potentially, the increase in the Earn is smaller because it may have a slightly flashier regime whereby the water levels rise and fall more quickly so the number of days spent at a 1:2 year flow is lower than in the bigger catchments of the Dee and Spey. Despite the Almond being a smaller catchment it is more forested and has less agricultural land making the catchment less sensitive to rainfall, with possibly a slower rise and fall in river flow levels. The pre-climate change enhanced flow record for the Earn showed a shift towards a drier period from 1957 which is no longer present suggesting that the number of days a 1:2 year flow occurs is more consistent throughout time. The Findhorn and Clyde both show a statistically significant upwards trend of an increasing number of days in which a 1:2 year flow occurs and also a statistically significant change towards an increase in the number of days that a 1:2 year flow occurs, which was not present pre-climate change. This shift occurred 10 years earlier in the Findhorn compared to the Clyde with the mean number of flows annually going from 1.34 to 3.42 and 1.59 to 4.09 respectively.

The results suggest that the behaviour pattern of these rivers could move towards a more hydrologically active flood regime. There is also the potential that this statistically significant shift in the hydrological regime between a pre-climate change record and post-climate change record will result in some sort of morphological adjustment of channel reaches as they react to changes in the erosion and sedimentation rates (Macklin and Lewin, 2003).

Table 2.17 Increase in Channel Dimensions required to convey a 1:2 year flow under a climate enhanced flow record

River	Percentage Increase in Channel Depth	Percentage Increase in Channel Width
Almond	10.50%	7.98%
Clyde	10.42%	8.15%
Dee	12.27%	9.50%
Earn	10.20%	7.90%
Findhorn	0.42%	11.00%
Spey	6.86%	5.42%

Each river will react differently depending on the surrounding land use and cover, freedom of the channel to adjust, human interaction with the channel, its location within the catchment and more localised changes in precipitation and sediment transfer (Coulthard et al., 2005). If the frequency of the current 1:2 year flow increases as has been put forward here (almost a halving in the number of days between flood peaks) then there will be less time for the channel to recover between 1:2 year flows, and as result the channel will begin to evolve and adjust its morphology to allow it to accommodate and convey a larger 1:2 year flow or dominant discharge. Hey and Thorne (1986) obtained regime-type relationships to predict bankfull dimension based on discharge using 62 gravel-bed rivers in the UK. Although these empirical formulas were originally intended for working out the bankfull dimensions for designing stable mobile gravel-bed rivers, they can be used here to calculate difference in channel size required to convey a 1:2 year flow pre- and post- climate change. On average the channel width increased by 10%, (Table 2.17) and depth by around 8% for the rivers studied here. When compared to Gilvear's 2004 study looking at channel adjustment on the Spey post impoundment channel width above the dam was found to have increased by 3% (1989) and 9% (1995)

since 1901 due to an increased frequency and magnitude of floods, thus a move towards 10% increase in channel width over next years does not seem unreasonable. Rivers which continue to display shifts between ‘flood-rich’ and ‘flood-poor’ periods (Almond, Clyde, Findhorn and Spey) could potentially go through periods of accelerated and decelerated channel adjustment as was found to be evident on the Spey whereby channel narrowing was found to accelerate during flood-rich periods (Gilvear, 2004).

An enhanced hydrological regime will also potentially adjust sediment delivery into the channel and sediment transfer within the channel, two important variables in the development of channel morphology (Thorne, 1997). The effect of changing sediment and hydrologically regimes has been well document in the literature (Harvey, 1969; Schumm, 1977; Hey and Thorne, 1986; Park, 1995; Sear, 1996; Werritty et al., 1997; Kondolf et al., 2002; Raven et al., 2010) and is summarised in Table 2.18. Stover and Montgomery’s (2001) study looking at channel change on the Skokomish River in Washington found that an altered stage-discharge relationship whereby peak-flow was decreased and sediment delivery to the channel was increased caused channel aggradation resulting in a shallower channel and greater floodplain inundation from smaller peak flows. In the UK Lane et al. (2008) found that climate change was likely to increase sediment delivery to a river, resulting greater in channel aggradation and thus increased flood risk in the affected areas.

The sensitivity of each river to these changes will vary due to difference in geology and catchment size but as studies (Knox, 2000; Coulthard et al., 2001; Macklin and Lewin, 2002; Coulthard et al., 2005) have shown, land use and cover are often found to be the main driver in amplifying and damping changes in sediment transfer caused by a changing hydrological regime.

Table 2.18 Channel Response to Changes in the Hydrological and Sediment Regime of a River (adapted from Sear, 1996, after Schumm, 1969)

Changing Variable	Morphological Response				
	Width	Depth	Slope	Sinuosity	Dominant Mode of Sediment Transfer
Increase Q	Increase	Increase	Decrease		Degradation
Increase Qs	Increase	Decrease	Increase	Increase	Aggradation
Increase Q and Qs	Increase	Increase/Decreased	Increase	Increase	Current Process Intensifies
Decrease Q	Decrease	Decrease	Increase		Aggradation
Decrease Qs	Decrease	Increase	Decrease	Increase	Degradation
Decrease Q and Qs	Decrease	Increase	Decrease	Increase	Current Process Intensifies
Increase Q and Decrease Qs	Increase/Decreased	Increase	Decrease	Increase	Degradation
Decrease Q and Increase Qs	Increase/Decreased	Decrease	Increase	Decreases	Aggradation

key: Q = channel discharge; Qs = sediment discharge

There is also the possibility that certain areas within the river catchment will be more sensitive to channel adjustment than others. These 'hot spot' areas are locations within the river channel that are particularly sensitive to imbalances in sediment and water inputs causing the channel adjustment via degradation, aggradation or migration (Czuba and Foufoula-Georgiou, 2015). Depending on the changes in the interaction between an enhanced flow regime, sediment delivery, sediment transfer and the ability of the channel boundary to adjust in some rivers there could be the potential for a geomorphic threshold to be crossed, resulting in larger scale channel adjustment. However, the answer to this question lies in more detailed modelling of catchment processes.

Future changes in land use could also considerably amplify or mute the suggested trends and patterns in the frequency of high flow and number of high flow days. For example, when Macklin and Lewin (2002) investigated Holocene changes in flooding it was found that rivers varied in their sensitivity to climate change due land cover changes, predominately conversion of forestry to grasslands. Land cover changes such as this not only increases run-off but also sediment supply leading to increased channel aggradation, therefore making the channel more responsive to changes in the flow regime as a result of climate change (Coulthard and Macklin, 2001; Macklin and Lewin, 2002). This has been demonstrated on the River Wharf in Yorkshire where by short-term (16 months) sedimentation increased the magnitude of floodplain inundation for a 1:2 year flood to the same level expected by 2050 with climate change (Lane et al., 2008; Lane, 2008). Furthermore, Lane et al., (2008) found that by increasing forest cover to around 5% could reduce annual course sediment transfer rates by around 85%. This not only supports the work of Knox (2000) and Macklin and Lewin (2002) but highlights how relatively small land cover changes cannot only considerably reduce sediment delivery but also catchment sensitivity to climate change. When this is considered in relation to the patterns in the flood record found here it suggests small changes in land cover such increasing afforestation in the future could result in the enhanced 'flood-rich' and 'flood-poor' periods or significant trends towards increasing number of flood days becoming more muted.

2.4.3 Patterns and Trends in a Bedload Mobilisation Pre- and Post- Climate Enhanced Flow Record

As sediment transfer within a river channel is one of three main drivers in channel change (Thorne, 1997; Knighton, 1998; Montgomery and Buffington, 1998; Kondolf et al., 2002; Raven et al., 2010) it is important to understand how the patterns of sediment transfer change overtime and also how climate change will affect these patterns. Many problems in river management stem from the difficulty in predicting sediment behaviour during high flows (Reid et al., 1997). As a result, here we have looked specifically changes in the frequency of bed mobilisation for a 63 mm pebble which is close to the modal size of armoured river bed (Shih and Komar, 1990) to investigate potentially how frequently an armoured bed, often important for ecology, have been disturbed throughout the flow record of the rivers investigated here.

The number of days between the bed mobilisation in the Almond and Clyde both show one significant shift within their record. However, in the Almond the trend is towards an increase in the number of days between flood periods, suggesting bedload activity has decreased since 1962. This trend contradicts the flow records in which a decrease in the number of days between floods was found. The number of records for pebble movement is greater than the number of 1:2 year flow peaks which suggests that the flow required to move a 63 mm pebble is lower than bankfull discharge. Therefore, the drought conditions that occurred in 2004 to 2006 and 2010 to 2012 (Marsh, 2004; Marsh et al., 2007; 2012; Kendon et al., 2013; Hannaford, 2015) may have impacted lower more frequent flow required for bedload movement than the less frequent 1:2 flow. The Clyde, which is further west than the Almond, was less effect by the drought conditions in the of the 2000s and showed a similar trend to the flow record in that it showed a shift in 1977 towards an increased frequency of bedload movement. This complements previous studies which suggest higher winter flows since 1960 due to a move towards a more positive NAO (Wilby et al., 1997; Hannaford and Marsh, 2008).

The Dee and Earn show the same number of shifts as the number of days between 1:2 year flood peaks at three and two shifts respectively, but the timing of these shifts is different (Table 2.8 and 2.11). In both the Earn and Dee, the shifts in bedload movement occurred earlier than in the flow record and the number of days between bedload movement was generally much less than in the flow record. This suggests again that the flow required to move a 63 mm pebble in these rivers is less than bankfull and thus has potentially been more sensitive to small changes in land use (Macklin and Lewin, 2002) and climate variability. Findhorn and Spey show no significant shifts in bedload movement, but the Findhorn does a show significant downwards trend in bedload movement, potentially all being affected by drought conditions in that area during the 2000’s. Under a climate enhanced record only the longest of all the flow records here continues to show significant shits in bedload movement, although the move towards a drier period shift around 2000 is no longer present. Consequently, like the frequency of high flows, patterns in bedload movement over time will potentially be more consistent with shifts between more and less geomorphologically active periods much more muted. However, as mentioned above as the river is likely to adjust its morphology to allow it to handle a more active sediment and hydrological regime, these abrupt shifts and step-changes in bedload movement may return again in the future.

The number of days in which bedload was active in the Almond and the Clyde showed a significant shift towards an increase in number of day bedload is moving. Although in the Almond this occurs seven years later than in Clyde, potentially due to the Almond being further east so less effected by the westerly weather streams and differences in land use and cover. The Earn however still shows a dip in bedload activity from 1964 to 1989 in line with the perceived 'flood-poor' periods in the UK (Werritty and Leys, 2001). Under a climate enhanced record only the Clyde and Dee suggest a potential step-change towards increased bedload movement in the future. However, all rivers do show an increase in the mean number of days bedload will be active annually in the future, suggesting a greater ability of the river to move and deposit sediment. The Findhorn showed a significant upwards trend in the number of days bedload was active both pre- and post- climate change. This trend of increasing high flows over time, again ties in with the trend that since 1960 the UK has experience a more positive NAO (Wilby et al., 1997; Hannaford and Marsh, 2008; Brigg and Atkinson, 2011) and an increased number of atmospheric rivers (Lavers et al., 2011; Hannaford, 2015) bring increased rainfall to the UK.

Changes in the frequency at which bedload is mobilised either with climate change or during 'geomorphologically-active periods' may have an impact on the efficiency of the river to transport bedload through the system, by changing the frequency of 'bedload-pulses' (Gomez et al., 1989; Hoey, 1992; Knighton, 1998, Thorne et al., 2010). During periods of low geomorphic activity, the river bed will consolidate and form a stable bedload matrix, meaning that to initiate the movement of pebbles the river requires more energy, and therefore bedload movement occurs mainly during the recession limb of the next flood-pulse (Reid et al., 1985). However, during periods where bedload movement is occurring more frequently the fabric of the river bed will be looser and less consolidated meaning less energy is required to transport the sediment, so bedload movement starts during the rising limb and continues for a longer period of time. Reid and Frostick showed this in their 1986 study, whereby the stream power required for bedload transport at the end of a flood was only 20% of that required to initiate motion at the start of the flood. These 'bedload-pulses' are not entirely effected by the consolidation of the river bed but also sediment input into the channel and in-channel bedforms such as bars and pebble clusters (Cudden and Hoey, 2003; Cui et al., 2003). When this is considered along with changing patterns in bedload mobilisation it suggests that during times of increased movement less energy will be required to move bedload and thus the movement of bars downstream could be accelerated, and changes in the armoured layer of the river could become more frequent. However, as discussed above, this will also depend on the sediment inputs into the channel from the surrounding catchment. This illustrates the complexity and difficulty of looking at patterns in bedload mobilisation and changes in the frequency of floods and potentially what this means for the geomorphology of a river.

2.4.4 Future Management of River Systems

The patterns in flood frequency observed in this study highlighted that river channels do under-go significant shifts in their ability to transport and erode sediment, and these changes can occur within a human time scale of a few decades. River managers therefore need to consider this when modifying channels for flood mitigation, reducing degradation and aggradation, and restoring channel to improve ecological status. As Thorne et al., (2010) highlight one of the principle objectives when restoring a river channel is to ensure the delicate dynamic balance between sediment supply and bedload transport is restored to ensure a stable channel. However, as is highlighted here this balance can fluctuate over decadal time scales between times of increased and decreased sediment load and/or the ability to transport material, and thus, to ensure the long term stability of the reach both scenarios should be considered. Furthermore, when reinstating a channel back to a more natural channel morphology, managers potentially should consider that it may need to convey larger flood flows than it has in the past and the stabilisation of new banks with maturing riparian vegetation may take longer due a reduced recovery time between high flow events. Additionally, farmers and land managers who work the surrounding floodplains will potentially need to adapt their farming practices to allow for increased reworking of the floodplain and increased floodplain inundation than during previous decades. However, this will rely on the changing patterns in flood risk being perceived and accepted by farmers, which is often not the case (Pivot and Martin, 2002). At present there is limited research investigating the effect that the patterns in high flows shown here could have on agricultural practices in Scotland, both currently and in the future, and how changes in flood risk to agricultural land could be reduced. Future increases in urbanisation and built infrastructure, resulting in a greater coverage of impermeable surfaces, could also potentially amplify the trends and patterns found here (Falloon et al., 2010). However greater implementation of Sustainable Urban Drainage Systems (SUDS) and construction of storage reservoirs to attenuate flows may slightly reduce the amplified effect of increasing urbanisation and built infrastructure (Wheater and Evans 2009).

2.5 CONCLUSIONS

There is evidence to suggest that the frequency of geomorphologically effective flows has fluctuated between 'flood-rich' and 'flood-poor' periods and that over the last 10 to 20 years there has been a move towards a more flood-rich period with an increased frequency of high flows. This is consistent with previous studies (Werritty et al., 2002; Pattison and Lane, 2011; Wilby and Quinn, 2013) which have suggested that the flood record in the UK exhibits a non-stationary behaviour. The flood record shows fluctuations between periods of increased and decreased flood activity and also an increased frequency of high flows over the last 50 years due to a shift towards a more positive NAO. This would mean that the rivers would potentially go through periods of increased and decreased geomorphic activity and channel change, as changes in the hydrologically regime will potentially alter sediment delivery and transfer patterns and rivers ability to adjust its boundary. A climate enhanced flow record suggests generally that the frequency of geomorphic floods will almost double, as will the number days a geomorphic flood occurs, and the difference between 'flood-rich' and 'flood-poor' periods will be much more muted. Theoretically, this could lead to Scottish rivers being more active than they have been in the past, with a reduced recovery time between floods leading to an adjustment in their morphology to allow them to convey larger volumes of water and sediment, potentially crossing a geomorphic threshold. The sensitivity of different catchments to an enhanced hydrological regime with climate change will likely vary due to differences in land use and cover either intensifying or kerbing the effect of increased sediment delivery and potential morphological adjustment. Consequently, when undertaking future river management projects, it needs to be taken into consideration that Scottish rivers over the next 100 years will potentially be going through a transition period as they adapt to a new hydrological and sediment regime.

2.6 SUMMARY

- CUSUM analysis on six rivers across Scotland provides evidence to suggest that over the last 50 to 80 years Scotland has gone through ‘flood-rich’ and ‘flood-poor’ periods.
- Based on a medium emissions scenario for 2080 (Kay et al., 2011) there could potentially be a significant increase in the frequency and number of 1:2 year flows, and in most cases muting or damping effect on the difference between ‘flood-rich’ and ‘flood-poor’ periods.
- Catchments sensitivity to future changes in flood frequency will most likely be a result of land cover and land use.
- Future management strategies will need to take into account that they are potentially managing a changing system with greater flood frequency and sediment input than in the past few decades.

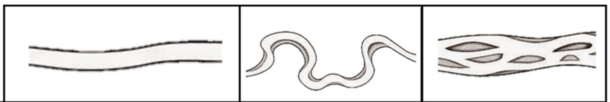
CHAPTER 3

Stream Power Divisions – an appropriate screening tool for channel stability in Scottish river channels?

3.1 INTRODUCTION

As the demands on river channels for human water supply, energy and flood prevention increases within a changing climate, the requirement for effective screening tools to predict changes in channel stability also increases. Stream power is one method which can be used to predict channel adjustment within river channels. This chapter explores the further use of stream power as a quantitative method for predicting changes in channel stability.

To manage and restore river channels effectively, river mangers need to have a firm understanding of the driving variables (sediment transfer, discharge and channel boundary characteristics) responsible for different channel morphologies, and the effect of changing external factors such as climate and land use on these main drivers (Raven et al., 2010). The morphology of a river channel is constantly adjusting and evolving in response to changes in the processes of sediment erosion, deposition and transport, allowed for within the constraints of the channel boundary (Thorne, 1997). These processes are altered through time due to changes in flow conditions and the sequence of flow conditions (normal flows, low flows, flood flows) associated with the inherent climatic variability of the region and changes in regional and local climate, as well as sediment input into the channel through changes in land management practices (Lane et al., 1996; Thorne, 1997; Raven et al., 2010). Traditionally, the morphology of alluvial river channels has been spilt into three distinct planform categories, namely, straight, meandering and braided (Leopold and Wolman, 1957), with distinct differences in flow strength, bank erodibility and sediment supply for each type, as illustrated by Knighton and Nanson (1993) (Figure 3.1). Later in 1963 Schumn created a river classification system based on channel stability and mode of sediment transport where by river channel reaches where separated into stable, eroding and depositing. Others (Culbertson et al., 1967) have developed more descriptive classifications looking at a number of channel features such as vegetation, sediment deposition, sinuosity, bank type and levees, and floodplain types. More recently channels have been classified by linking channels with similar forms and processes, and describing channel types using specific features, leading to classes such as cascade, step-pool, pool-riffle and plane bed (Rosgen, 1994; Montgomery and Buffington, 1997; 1998; Knighton, 1998). The basis of Montgomery and Buffington's classification is on the balance between sediment supply and transport capacity within a channel reach. Another recent approach used to classify river channels is the 'River Styles' approach developed by Brierley and Fryirs (2000; 2002; 2005; 2013) which aims predict channel behaviour. The River Styles



Channel Type	Straight	Meandering	Braided
Flow Strength	Low	Medium	High
Sediment Supply	Low	Low/Medium	Medium/High
Bank Erodibility	Low	Low/Medium	High

Figure 3.1: Difference in the driving variables associated with straight, meandering and braided channels.

framework links reaches together which have a similar character and behaviour resulting from similar catchments, landscapes, reaches and geomorphic units; rather than 'pigeon holing' river reaches into a specific channel type. Using this approach provides a method to describe and explain the forms and processes seen within the channel and how channel behaviour may adjust in the future (Brierley and Fryirs, 2005).

The direction of change within channel morphology will be governed by how each channel reach responds to changes in sediment supply and discharge and how the surrounding channel boundary can accommodate these changes (concept of degrees of freedom; Hey et al., 1978). For example, in a study on the lower Duchesne River, Gaeuman et al., (2005) found the response of gravel-bed reaches to a 50% reduction in stream flow and an increase in fine sediment supply was channel narrowing, whereas sand-bed reaches responded with aggradation and avulsions. Gaeuman et al., (2005) later found that increased flood magnitudes caused channel widening and secondary bed aggradation in gravel-bed reaches, but a narrowed highly incised channel in the sand-bed reaches. While Kondolf et al., (2002), when investigating reforestation in the Drôme River catchment (France), showed a reduction in sediment supply caused a reduction in channel width for an alluvial channel of 60% over a 23 year period and the colonisation of channel bars. Van den Berg, (1995) highlighted the importance of the channel boundary in his analysis of braided rivers. He found that rivers with greater boundary resistance where less likely to braid as a result of high stream powers. In the River Spey in Scotland Gilvear (2004) highlights the role of humans in channel change when he showed that the river had undergone aggradation as a result of upstream impoundment reducing flood magnitudes and sediment supply. Although, as the studies above demonstrate, the response of the different river channels to changes in these variables has been well documented (Harvey, 1991; Gilvear and Winterbottom, 1992; Gilvear and Bradley, 1997; Winterbottom and Gilvear, 2000; Coulthard and Macklin, 2001; Stover and Montgomery, 2001; Coulthard et al., 2005; Lane et al., 2008, 2007), the ability for river managers to predict where and when channel adjustment will occur is still challenging, due to the complex interactions between these controlling variables within areas of different geologies and landscape histories, e.g. glaciation, land use and land management practices. This is complicated further when rivers are viewed as systems operating within a state of equilibrium that exhibit threshold behaviour (Knighton, 1998). These thresholds, between one channel form and another channel form, are often fuzzy boundaries or thresholds (Schumm, 1977, 2003) due to the wide variety of different parameter thresholds which govern channel morphology, namely slope, sediment input, discharge, sediment calibre, bank material and riparian vegetation. In addition, the sensitivity of the channel to change needs to be considered (Brunsden and Thornes, 1979; Brunsden, 2001) as two rivers which have similar channel morphologies could react differently to a similar change in sediment supply if one channel happens to sit closer to a threshold than another, thus a smaller change is required to 'push it over the edge' into a new channel form (Sear and Newson, 2010). This means that river managers must not only understand how a river channel reach may change in response to different management practices, but also how sensitive the river reach is to these changes. Climate change now adds an additional dimension as it is expected that the magnitude and frequency of floods will increase over the next 100 years (Cameron, 2006; Jenkins et al., 2009) potentially increasing not only the ability of rivers to erode and transport sediment but also the sediment supply to the river. This will be of particular interest in river restoration projects and flood management schemes as not only will the current discharge and sediment regime need to be considered, but also the changes that would occur to these parameters with predicted climate change.

In Scotland, there are many bedrock-dominated river channels, which play a key role in controlling channels from upland sites (Bishop et al., 2005; Jansen et al., 2010; Castillo et al., 2013). These channels are an inherited feature within the Scottish uplands and remnants of its glacial past whereby glacial meltwaters cut into the bedrock leaving impressive gorges (Gregory, 1997). Bedrock channels are channels where over 50% of their channel boundary is exposed bedrock or is covered with an alluvial veneer which is mobilised during high flow events (Tinkler and Wohl, 1998). They tend to occur in reaches where channel gradient is significantly higher than adjacent alluvial reaches and stream power is greater than the critical stream power required for sediment transport resulting in high rates of sediment transport (Cray, 2010; Perfect et al., 2013). Within a river, long profile bedrock reaches are knick-points acting as base level controls within a catchment controlling upstream channel incision and gradient, downstream sediment supply from surrounding hillslopes and the transport of bedload material downstream (Allen et al., 2013; Whitbread et al., 2015). The presence of bedrock reaches throughout the long profile of Scotland's rivers means that they do not have a traditional concave shape where by slope gradually decreased downstream from the headwaters to its mouth. Instead it is made up of a series of concave segments as each bedrock-controlled section resets the systems or acts as a break in the system preventing the gradual decrease in slope and bedload size downstream and a natural peak in stream power within the pediment region (Gregory, 1997; Brierley and Fryirs, 2005). Morphological changes in bedrock channels resulting in a lowering of the channel base-level within a reach will have a knock effect on the alluvial channels downstream. This is because any base level changes will cause a change in slope, sediment supply and transport capacity, often leading to change in channel morphology (geometry and or planform). However, the rate of base level change is important. If the base level lowering occurs quickly, the river will incise with limited lateral migration, where as if base level lowering occurs slowly vertical incision will be reduced and lateral migration will occur (Schumn, 1993). The sediment transport processes and morphological change within bedrock and alluvial channels differs. Bedrock channel generally more efficient at transport sediment compared to alluvial channels (Hodge et al., 2011). Morphological change unlike alluvial changes is unidirectional (Tinkler and Wohl, 1998). Any base level lowering or channel widening is permanent whereas alluvial and gravel channels can aggrade, degrade and migrate over time meaning that changes in channel planform and geometry are often not permanent as they have the ability widen and narrow or increase and decrease their depth in response to changes in sediment supply and discharge (Tinkler and Wohl, 1998). When managing and restoring rivers the role of bedrock within the catchment needs to be considered. Furthermore, when predicting how channels will react to different management practices within and out with the channel, it should not be assumed that bedrock channels will behave in the same manner as alluvial channels (Tinkler and Wohl, 1998).

Historically, river managers have predicted how and why a river channel has evolved in a certain way by using detailed empirical observations and the use of regime theory and hydraulic geometry relationships (Nelson et al., 2003). However, despite being a powerful tool for predicting channel evolution, the development of these empirical relationships is data-heavy. The data required to make predictions on channel change has generally not been available. This means predictions are routinely based on extrapolation from catchments with similar characteristics (Nelson, 1996). This inevitably leads to increased uncertainty in the prediction of potential channel adjustment and thus potentially a poor management decision being made. More recently developments and advancements in hydraulic and sediment-routing models, and the increased availability of digital data sets have allowed river managers to predict channel form and adjustments resulting from changing sediment and flow regimes more accurately, and often without the requirement for intensive field surveys. These include multivariate logistic regression models such as that used by Downs (1995) on the River Thames looking at the catchment characteristics associated with different styles of channel adjustment, and reach scale models such as SIAM (Little and Jonas, 2010), a one-dimensional sediment continuity model used to predict the effect of local changes in flow and sediment regime on a series of river reaches; and finally, catchment scale models such as CAESAR (Coulthard et al., 2005) a cellular two-dimensional flow and sediment model which simulates channel adjustment on a flood by flood basis. Palaeohydrology techniques (McEwen, 1994; Sear and Arnell, 2006) where historical channel adjustment is investigated to provide insight into past channel adjustments are a popular means of predicting the sensitivity of rivers to different changes in environmental conditions. One method for doing this is the Channel Migration Zone (CMZ) method which using field surveys, aerial photography, remote sensing and a geographical information system to map the area where a river is susceptible to channel erosion (Rapp and Abbe, 2003; Olson et al., 2014). The assumption being that any previous channel migration is reflected within the channel, floodplain and valley bottom (Olson et al., 2014). In the US, the outputs from CMZ method are used to guide planning for housing developments, floodplain management and river restoration (Rapp and Abbe, 2003). However, in many cases using palaeohydrology techniques it can be difficult to establish the driving variables for the identified changes in channel morphology.

Although, the methods mentioned here used to predict channel change have proven to be effective and accurate when applied appropriately they can be time consuming processes and spatially can only be used on smaller sections of channel; although some models now, such as CAESAR (Coulthard et al., 2005) or ST:REAM (Parker et al., 2015), can be applied at the catchment scale. Thus at present it is proving difficult for river managers to gain a national scale prospective on the effect of climate change and changing flows on channel stability and the potential direction of channel adjustment, in a quick and efficient manner. An understanding of how a river may react to changes in climate nationally is important as it provides guide to where future management issues may arise in the future. This is important when making decision on where to focus restoration work and granting CAR (Controlled Activities Regulation) licenses. Using stream power as a screening tool is one method which can be used at the national scale for providing an initial decision on how sensitive individual river reaches are to change, and also whether the direction of change within that reach will be via deposition or erosion (Brookes and Wishart, 2006; Vocal Ferencevic and Ashmore, 2012). The stream power of any given reach is defined as the amount of kinetic energy available for the river to do work i.e. transport or erode sediment (Brookes, 1987b; McEwen, 1994; Petit et al., 2005) and as a result has been shown to have a significant influence on channel forms and processes (Fonstad, 2003).

The term was first used by Bagnold in 1966 when looking at sediment transport. However, since then a number of people have used stream power to define floodplains into high, medium and low energy types (Nanson and Croke, 1992), differentiate active and in-active meanders (Ferguson, 1981), explain occurrence of channel incision (Schumm, 1977) and to evaluate change in engineering and restoration projects (Brookes, 1987b). The advantage of using stream power is that it is relatively easy to calculate as its variables (slope, discharge and channel width) can all be collected using digitally available data, and it does not require velocity or channel depth which are hard to calculate or estimate without data from lengthy and time consuming field surveys. Slope can be measured using a digital terrain model, discharge using flow accumulation grids, and channel width using OS Master Map. Two different forms of stream power have been used in previous studies. These are ‘total stream power’ which gives the potential energy per unit length of channel, and ‘specific’ or ‘unit stream power’ which gives the potential energy per unit area of the channel bed (Brookes, 1987b, Knighton 1998, Brookes and Wishart, 2006). However, because total stream power is scale dependent, in that larger rivers will have higher stream powers than smaller rivers, specific stream power (power per unit area) is used more often (Thorne et al., 2010).

In the UK, stream power screening is used in river management as a rapid assessment tool to assess the likelihood of a river eroding or depositing sediment in response to channel management decisions (Brookes and Wishart, 2006). How a section of channel will respond to these changes is based on where the stream power of channel sits within a series of thresholds (Figure 3.2). These thresholds are based largely on the work of Brookes (1987a, b) who investigated straightened managed streams in Denmark and England and Wales. Brookes (1987a, b) found that river channels changed through depositional processes when stream power was less than 10 Watts m^{-2}, between 30 and 100 Watts m^{-2} streams would change through erosional processes, and above 100 Watts m^{-2} large scale channel shifting would occur (Table 3.1).

Table: 3.1: Specific Stream Power Thresholds for Predicating Channel Adjustment

Stream Power	Channel Adjustment
< 10 Watts m^{-2}	Deposition
> 35 Watts m^{-2}	Erosion
> 100 Watts m^{-2}	System recovery - lateral channel shifting

Although Brookes's (1987a, b) stream power thresholds are currently used as a means for screening for potential channel change, the thresholds proposed have been developed on managed channels within England and Wales, and not for high energy upland channels with differing boundary conditions like those found in Scotland, which have a different glacial history, geology and landscape to many places in lowland England and Wales. To ensure the development of a potentially more accurate screening tool, it would be advisable to investigate how these thresholds stand up when applied to Scottish river channels. Initial work looking at stream power thresholds in upland channels with coarse bed material like those often found in within Scottish landscapes focused on the threshold between braided and non-braided river channels in British rivers (Ferguson, 1981). Braiding and active low sinuosity channels were found to have stream powers of more than 100 Watt m^{-2} (median value 160 Watt m^{-2}) compared to inactive channels which tended to have stream power less than 60 Watt m^{-2} (median value 15 Watt m^{-2}) (Ferguson, 1981, 1987) (Figure 3.3). Active meandering channels were found to exhibit intermediate stream power values (median value 30 Watt m^{-2}). These higher stream power threshold values established by Ferguson (1981, 1987) for upland coarse bed river in Britain further highlight the need to review the use of stream power thresholds as a means of predicting changes in channel stability at the national scale.

The ability to do this could potentially be useful to river managers in allowing them to identify the areas where channel stability could be an issue in the future, so they can be more 'proactive' in ensuring that people living and working in these areas are aware of future risk, or work towards mitigating these risks. This study aims to investigate: (i) how relevant Brookes's stream power thresholds are within Scottish river channels, using SEPA's Digital River Network data, and (ii) how useful stream power thresholds are for predicting the effect of climate change on the morphological stability of Scottish river channels

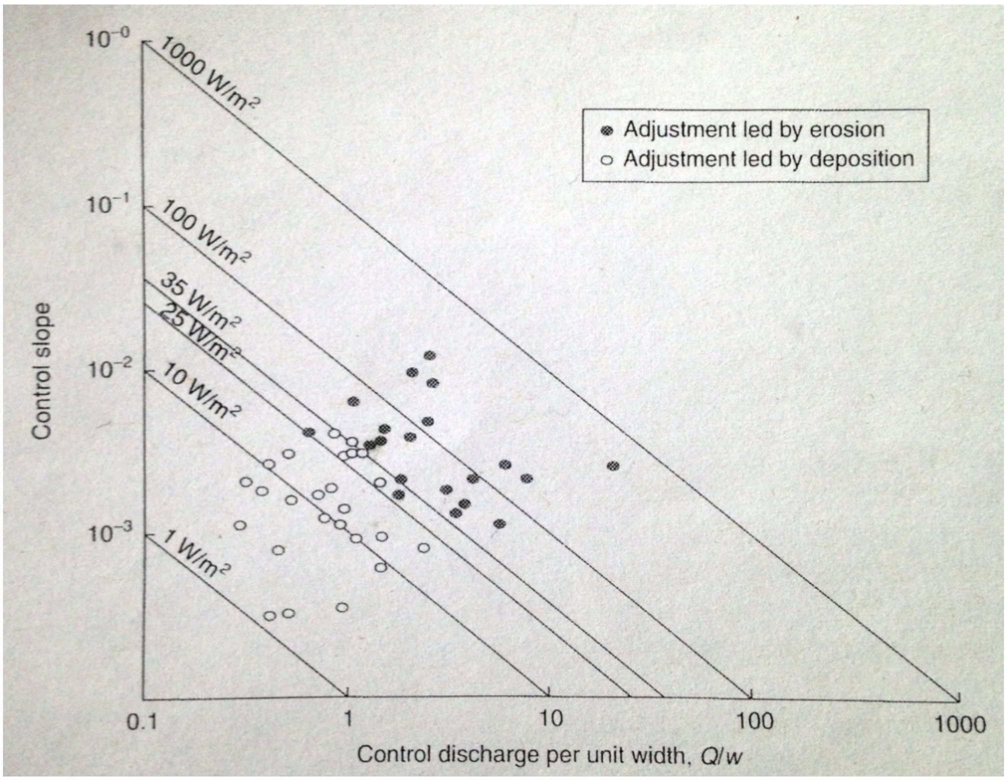


Figure 3.2 Plot showing the specific stream power of several UK river channels adjusting via deposition and erosion. As suggested by Brookes (1987b) above a specific stream power of 35 Watts m-2 channel adjustments are primarily through erosion, and below 35 Watts m^{-2} channel adjustment is primarily through deposition. Diagram taken from Thorne et al., 2010 (page 136)

3.2 METHODS

3.2.1 Field Survey Observations

Six Scottish rivers were selected to assess the relationship between stream power and river channel processes, namely sediment deposition, transport and erosion. The rivers which were selected covered a broad range of locations across Scotland, and had good field survey data, with mapped channel process types along the length of the entire channel. All rivers have a geomorphology that is strongly influenced by past glaciation and have limited artificial structures or managed river reaches. The rivers were: The Water of Bervie in Aberdeenshire, The Water of Ae and River Moffat in Dumfries, River Charnaig in Sutherland, and River Farnack and River Isla in Moray (Figure 3.3). The rivers selected were all upland gravel-bed rivers, with catchment areas ranging from 150 km^2 to 250 km^2. Field survey observations for all six rivers were carried out by SEPA (Scottish Environmental Protection Agency) geomorphologists, and included classification of each 50m reach into one of the six geomorphic process types. These were: erosional source, erosional exchange, balance exchange, balance transport, depositional exchange and depositional sink. Each process type describing coarse sediment transport processes which occur within river reaches. The criteria for the geomorphic process types of each river reach are outlined in Table 3.2. These process types were identified and defined by SEPA geomorphologist. Before use in this study these course sediment process types were review and were deemed a good description of course sediment transport processes within Scottish rivers. A total of 3393 50m reaches were surveyed across all rivers with 303, 337, 505, 583, 688 and 977 reaches in the Farnack, Charnaig, Bervie, Moffat, Ae and Isla respectively.

Table 3.2: Channel Process Types Descriptions

Source: Morphological Survey Field Training Manual. 2015. SEPA Hydromorphology Technical Group

Process Type	Description	Field Example
Erosion Source	• These reaches are dominated by processes of erosion. • There is little or no input of sediment at the upstream end of the reach. • Within the reach there is obvious erosion of the bed or banks (or both) resulting in significant input of sediment, which is then efficiently transported to the next reach downstream. • Storage of sediment within the reach is negligible or completely absent.	
Erosion Exchange	• These reaches are still dominated by processes of erosion but there is also obvious input of sediment from upstream. • Whilst erosion is clearly the dominant process, and the output of sediment from the reach is greater than the input, there is also an element of deposition within the channel acting as temporary storage. • This is often visible in the form of small bar features at channel margins.	

Process Type	Description	Field Example
Balance Exchange	• As implied in the process type description these reaches have roughly equal rates of erosion and deposition occurring within them. • The input of sediment from upstream is also roughly equal to the amount of sediment leaving the reach. • There will always be erosion and deposition features in these reaches, but the extent will depend on the morphological setting and the quantity of sediment input from upstream.	
Balance Transport	• These reaches are very efficient sediment transport reaches. • The sediment input from upstream is quickly transported through the reach, so that the output is roughly equal to the input. • There may be some mobile sediment temporarily stored on the bed of the channel between transport events. • These reaches are characterised by stable channel boundaries such as bedrock, boulders or large cobbles which rarely if ever move. • Any input of sediment from the reach is generally visually undetectable.	

Process Type	Description	Field Example
Depositional Exchange	• These reaches are clearly dominated by the processes of deposition • It is clear that some sediment is being transported downstream out of the reach. • Output of sediment from the reach will however be less than the input. • Also, there will almost always be bank erosion within the reach.	
Depositional Sink	• Reaches are dominated by processes of deposition. • Deposition of sediment will be clear and obvious with very little or none of the sediment entering the reach, exiting the reach. • Bank erosion will be present towards the upstream end of the reach but become less extensive towards the downstream end.	

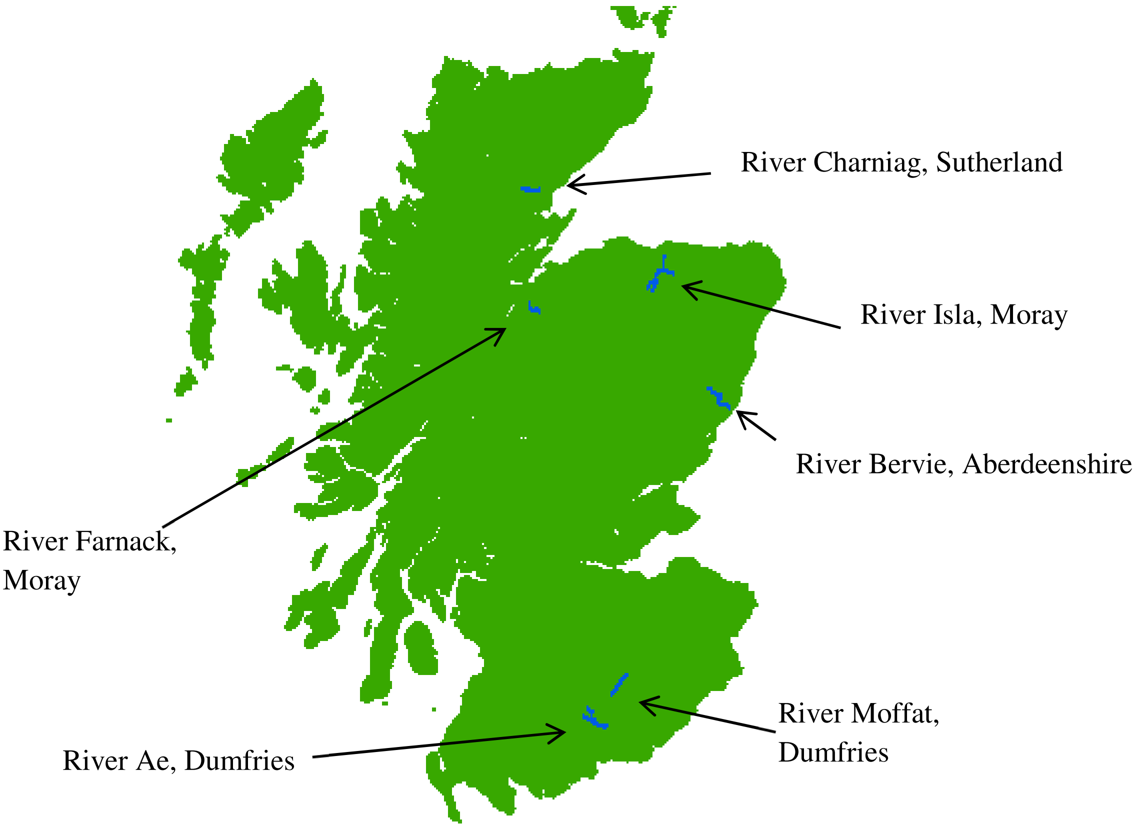


Figure 3.3 Location of study rivers across Scotland

3.2.2 Stream Power Calculations

SEPA's Digital River Network model was developed using ArcMap's geospatial processing platform and contains modelled channel data for every 50m river reach in Scotland (Greig et al., 2008). The river network consists of a series of centrelines depicted on an Ordnance Survey 1:25,000 mapping. For every 50m reach the channel slope, width, discharge (for a series of different flood magnitudes), sinuosity, confinement ratio and channel typology is recorded. In this study only the channel slope, discharge (Q_{MED}) and channel width were used. The channel width was obtained using the waterbodies OS Master Map polygon, whereby the perpendicular distance from the reach point to the either side of the Master Map polygon is measured and the total distance taken as the channel width (Matheson et al., 2008). Channel slope values were calculated using a NEXTMap 5m resolution digital elevation model (DEM) by horizontal slicing of the NEXTMap DEM (Reinfelds et al., 2004; Jain et al., 2006). This involves measuring channel slope at set distance as you travel downstream. Here the distance over which slope is measured is linked to stream order, whereby the window over which slope is measured is increased by 50m with each increase in stream order; so a slope of a first order stream is measured over 50m, second order stream 100m and third order stream a 150m and so forth. The Q_{MED} value was extracted from CEH (Centre from Ecology and Hydrology) flow accumulation grids which are derived using the Flood Estimation Handbook (Stewart et al., 2008). For more detail on the SEPA's Digital River Network see Greig et al., 2006a, b, c. The model-generated slope, discharge for a Q_{MED} flood and channel width from this model were used to calculate the specific stream power at each of the surveyed reaches. Specific stream power, the rate that potential energy that is supplied to a unit area of the river bed (Knighton, 1999), was calculated by:

$$\omega = \frac{\rho g Q S}{w}$$

Where Q is the discharge ($m^3 s^{-1}$), *w* is the width of the water surface in meters, *S* is the longitudinal slope in m m^{-1}, ρ is the specific weight of water, and g is the acceleration due to gravity in m s^{-2}.

Specific stream power was calculated using the median annual maximum (Q_{MED}) currently and under predicted climate change for a medium scenario by 2080. The climate change prediction was taken from UKCP09 projections where the HadRM3 was used to predict changes in regional climate (Murphy al., 2009). The Q_{MED} was used because a flood with a return interval of every two years has often been taken to be bankfull discharge and the flow responsible for a channels current morphology (Knighton, 1998). It is also a common metric used to depict stream power and used as a 'design flow', meaning many river structures or culverts are used designed to convey flows of this magnitude (Barker et al., 2009; Bizzi and Lerner, 2012). This would mean, if changing climate meant a river reach was no longer capable of conveying this flow, potential management problems could arise, and therefore it would be useful to know where these locations are.

For each 50m reach the relationship between channel slope and discharge (cumecs) per unit width was plotted against slope, and a line of equal stream power added to the diagram to allow a visual assessment of where each channel process type fell within the stream power thresholds of: 1, 10, 30 and 100 Watts m^{-2}. To establish if there were any clear thresholds between the channel process types discussed here, a box and whiskers plot showing the data range for all six channel process types was constructed. To ensure the results were not influenced by extreme values or outliners, the data was ranked by specific stream power value from largest to smallest. A Kruskal-Wallis test for nonparametric data was then carried out on the collated data set using the six reach types, using R Studio version 0.97 (R Development Core Team, 2012). This was done to establish whether there were statistically discrete groups within the six different process types established during field observations. A post-hoc test was then conducted to see which channel process types were different from one another. Process types shown to have no statistically significant difference were then grouped together into a single process type, and then renamed. These were: balanced exchange and erosional exchange, and depositional sink and depositional exchange, which were renamed ‘exchange’ and ‘deposition’ respectively. The box plot was then reconstructed using the new channel process groupings to look for clear thresholds between the channel process types. The Kruskal-Wallis and post-hoc testing was then repeated to ensure all channel process groups where statistically different from each other. Kruskal-Wallis and post-hoc testing suggested there was a statistically significant difference between the four new channel process groups of disposition, balanced transport, exchange and erosion. However, no clear thresholds could be established between these four new process groups. The decision was then taken to look just at depositional sink and erosional source reaches where a clear threshold between the two groups could be established. This is because within all other reaches, despite erosion or deposition being dominant, sediment is still being transferred within these reaches. However, within depositional sink reaches almost no sediment is removed from the reach, and with erosion source reach almost all sediment is removed, making these reaches the most interesting to managers as they cause potentially the biggest fluvial hazards. Areas where considerable sediment deposition occurs can increase flood risk for example a highly depositional reach near the town of Comrie, in Perthshire. Due to substantial amounts of sediment deposition the river has avulsed meaning the river is closer to the town and floods nearby housing during high flow events (Personal communication SEPA). Similarly, new infrastructure such as bridges would not get a licence to be built in reaches where high levels of erosion are predicted to occur. The box plot was therefore redone using only the erosional source and depositional sink process channel types. The Quartile 3 specific stream power value of the depositional sink reaches was taken to be the upper thresholds for depositional reaches. Thus it would be assumed that any reach with a specific stream power below this value would be considered to be undergoing change via depositional processes, which have the potential to cause the greatest fluvial risks. For the erosional source process reaches the Quartile 1 specific stream power value was taken to be the lower threshold for predicting erosional reaches. Thus it was assumed that any reach with a specific stream power above this value would undergo channel change via erosional processes that have the potential to cause the greatest fluvial hazards. Any reach with a specific stream power between these values would be expected to undergo some form of sediment transfer but it would not be known whether the reach was erosion dominant, deposition dominant or transfer dominant; however it could be assumed that these reaches pose a lower fluvial risk than the erosional and deposition reaches. This approach to establishing stream power thresholds is based on taking a risk-based approach to predicting the channel process types; whereby, confidence in the prediction is greater below the Q3 specific stream power value for deposition and above the Q1 specific stream power value in erosional reaches, but less for stream powers between these values. The accuracy of the suggested thresholds was then tested in Excel by comparing the modelled channel process types suggested using the stream power thresholds, against those identified in the field. This was completed for both the threshold values suggested here and those suggested by Brookes (1987a, b). To do this the six original groups were grouped in two different ways. First, into erosion (erosional source, erosional exchange, and balanced exchange), exchange (balanced transport) and deposition (depositional sink and depositional exchange), and then into erosion (erosional source and erosional exchange), exchange (balanced exchange and balanced transport) and deposition (depositional sink and depositional exchange), to see which was most accurate.

To calculate a simple threshold between high energy and low energy channels, or rather reaches in which erosion is dominant and those in which deposition is dominant, a box plot was constructed of the of depositional sink and depositional exchange grouped together to create a ‘depositional group’ (because there is a statistical difference between them), and then the erosional source group. The erosional exchange group was not combined with the erosional source group because it was found to be statistically more similar to the balanced exchange reach. The six process types were then spilt into two: erosional (erosional source, erosional exchange, and balance exchange) and depositional (balance transport, depositional exchange, and depositional sink), and the accuracy in predicting channel types tested and compared with the Brookes thresholds.

The Scottish Digital River Network model, with a specific stream power value for each reach, was then used to calculate how many reaches fell into each threshold category and also the number of reaches which sat close to a particular threshold. This was done using the new thresholds devised here and also the original thresholds devised by Brookes (1987a, b).

3.2.3 Application and Predicting Climate Change Impacts

To assess the sensitivity of Scottish rivers to climate change the number of reaches which crossed a threshold from one process type to another as a result of climate change enhanced flows was calculated. This was done for the thresholds developed in this study and for the thresholds developed by Brookes (1987a, b). The increase in specific stream power associated with a flood with a return interval of every two years under climate change was calculated using the predicted increase in river flows for river basins across Scotland outlined by the Centre for Ecology and Hydrology (Kay et al., 2011) under medium emissions scenarios by 2080. This method was chosen, as the percentage increase in flow values takes into account catchment characteristics (geology, soil type, and land use) and not just the increase in rainfall, and therefore was deemed to be more accurate. The rivers across the whole of Scotland were split by area into: north, west and east Scotland; and the average percentage increase of a one in two-year flow for each river basin within the three areas was calculated. The percentage increase in flow taken was based on a worst-case scenario for medium emissions by 2080. This equates to a 90% chance that an increase in flow would not be greater than that value. The percentage increase in flow for the east of the Scotland was the average of: the north-east catchments, the Tay catchment, the Forth catchment and the Tweed catchment, and worked out as a predicted 33% increase flow. In the west of Scotland, the projected increase in flow was taken as the average increase for: the Solway, the Clyde and the Argyll fluvial areas, and worked out at a predicted 43% increase. The north of Scotland had a projected flow increase of 41% based on flow increases for the west highland and the north highland river catchments. The one in two-year discharge value for each reach was then increased by the percentage associated with each Scottish zone it was located within. The specific stream power for all reaches was then recalculated.

3.3 RESULTS

3.3.1 Stream Powers in Scottish Rivers

Specific stream powers across Scotland based on the data from SEPA's Digital River Network, were found to range from 1 to 14,000 Watts m^{-2}, with an average of 650 Watts m^{-2}. The maximum, minimum and average specific stream power for the Isla, Moffat, Bervie, Ae, Farnick, and Charnaig are shown in Table 3.3.

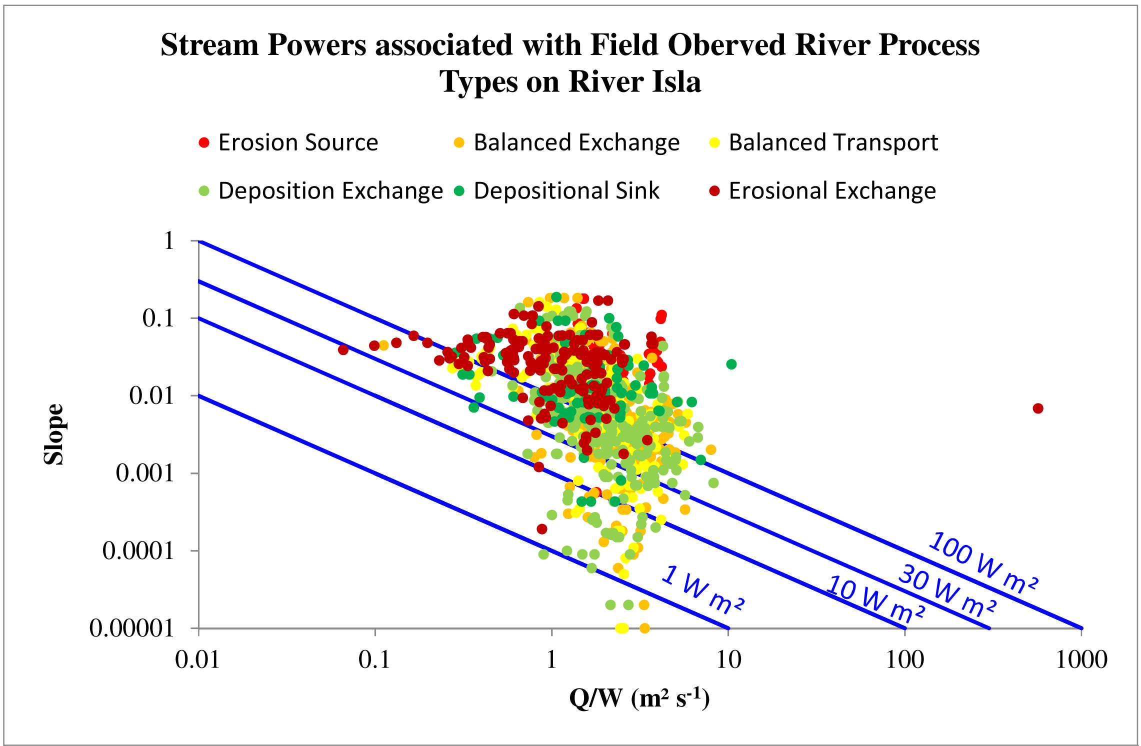
Table 3.3 Stream Power Statistics for each River

River	Minimum Stream Power Watts m-2	Maximum Stream Power Watts m-2	Average Stream Power Watts m-2
Isla	4,560	0.24	350
Moffat	7,910	3.62	860
Bervie	4,825	0.97	500
Ae	11,769	1.5	850
Farnick	2,436	0.93	160
Charnaig	2,344	1.9	300

Figures 3.4, 3.5 and 3.6 shows the relationship between channel slope and discharge per unit area for each of the six catchments investigated here, and Figure 3.7 shows the data from all catchments grouped together. Across all rivers very few erosional reaches are located at stream powers below 100 Watts m^{-2}, suggesting that in most cases a stream power in excess of 100 Watts m^{-2} is required before erosional processes dominate within a reach (Table 3.4). In the Water of Ae and Moffat Water, 89.1% and 83.2% of all reaches had a stream power of above 100 Watts m^{-2}, potentially because they have catchment areas between 200 km^2 and 300 $km^{2,}$ making them, in Scottish terms, relatively large catchments. Magilligan (1992) found on the Galena River in Wisconsin that specific stream power peaks during extreme flood events in catchments which have a drainage area of between 200-300 km^2. In the Farnack, Bervie, Isla and Charnaig over 70% of reaches had a stream power in excess of 35 Watts m^{-2} which, based on Brookes's

(1987a, b) stream power thresholds, would suggest erosional process dominates in these catchments; a prediction not observed in the field. When the figures from all reaches are collated, over 75% of all reaches surveyed (Figure 3.8 and Table 3.9) had a stream power in excess of 100 Watts m^{-2}, which, based on the thresholds set out by Brookes, would suggest a large number of laterally dynamic reaches within the rivers surveyed here. Only 4% of reaches surveyed had a stream power of less than 35 Watts m^{-2} and thus would be considered to adjust via depositional processes. During a flood with a return interval of every two years 86%, 72% and 77% of erosional, balanced and depositional reaches respectively had a stream power value of greater than 100 Watts m^{-2}.

When looking at the stream powers for the six different channel process types it would be expected, under thresholds outlined by Brookes (1987a, b), that erosion dominant reaches (erosional source and exchange) would predominantly have stream powers greater than 35 Watts m^{-2}, balanced reaches (balance exchange and transport) would predominately have stream powers between 10 and 35 Watts m^{-2} and deposition dominant reaches (depositional exchange and sink) would predominately have stream powers below 10 Watts m^{-2}. However, for the river reaches investigated here, reaches with stream power in excess of 100 Watts m^{-2} were most common across all observed channel process types (Figure 3.7). The data collected here therefore suggests that the current thresholds used for predicting the direction of channel adjustment in the upland channel of Scotland are too low and thus potentially the thresholds need to be revisited for use in Scottish river reaches.



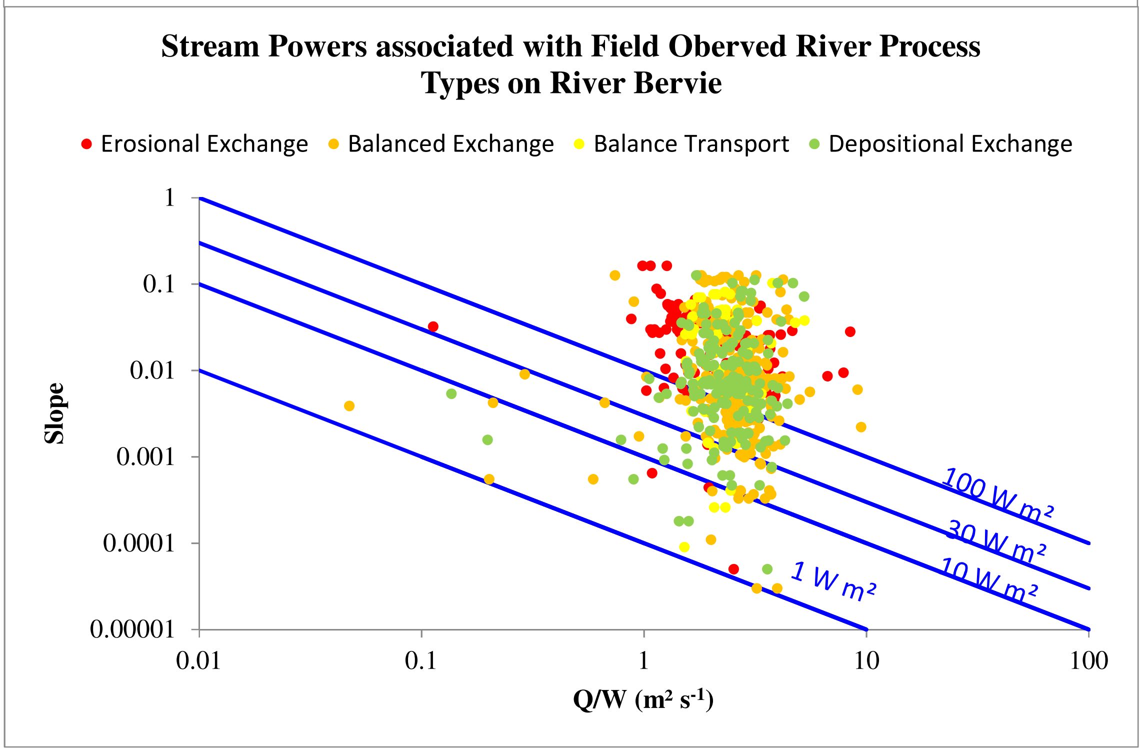


Figure 3.4 Specific stream power plots showing the stream power associated with different channel process type for the River Isla and River Bervie. Erosional processes types are shown in shades of red, balanced process types in shades of yellow and depositional process types in shades of green to help establish a more simplified picture of channel processes.

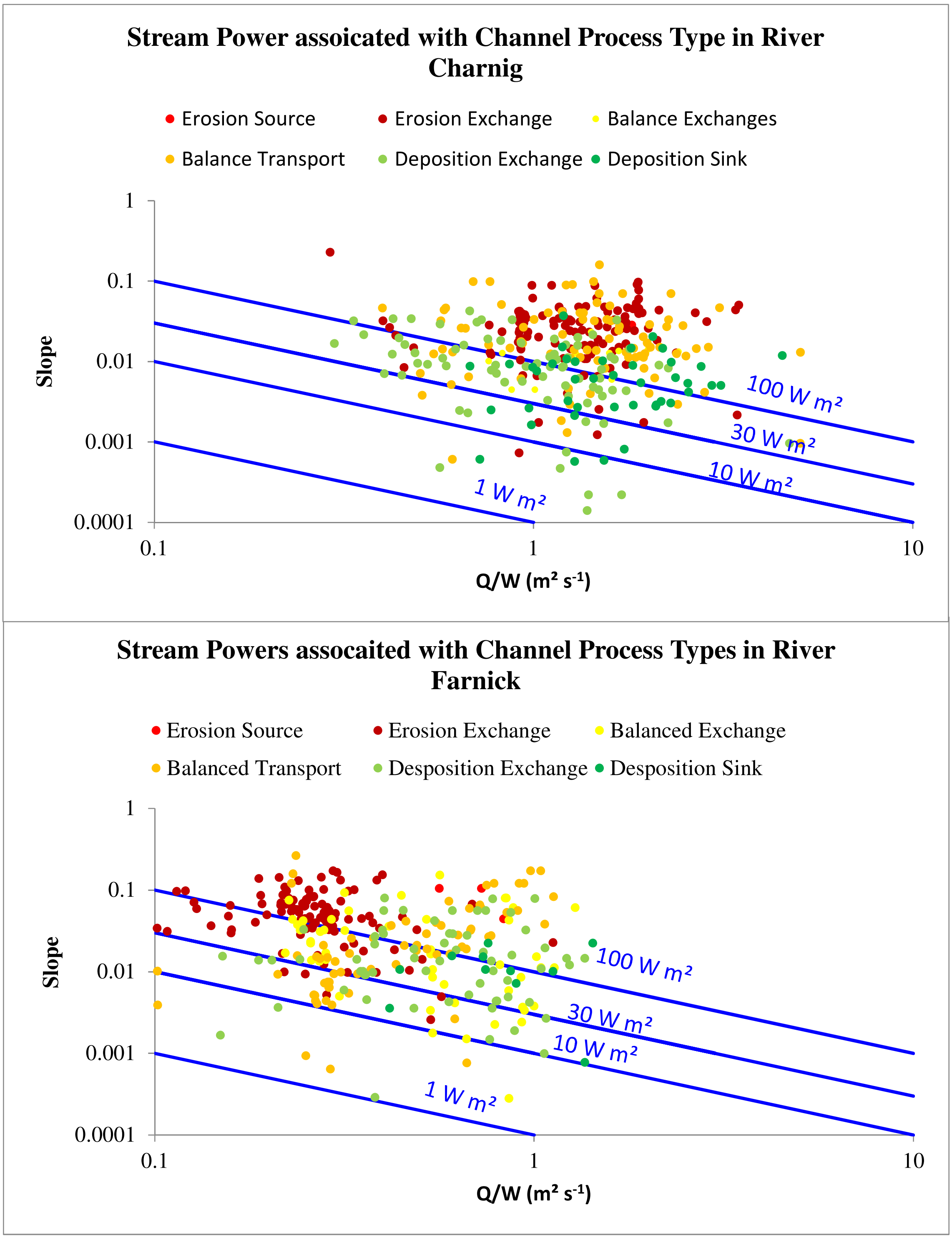
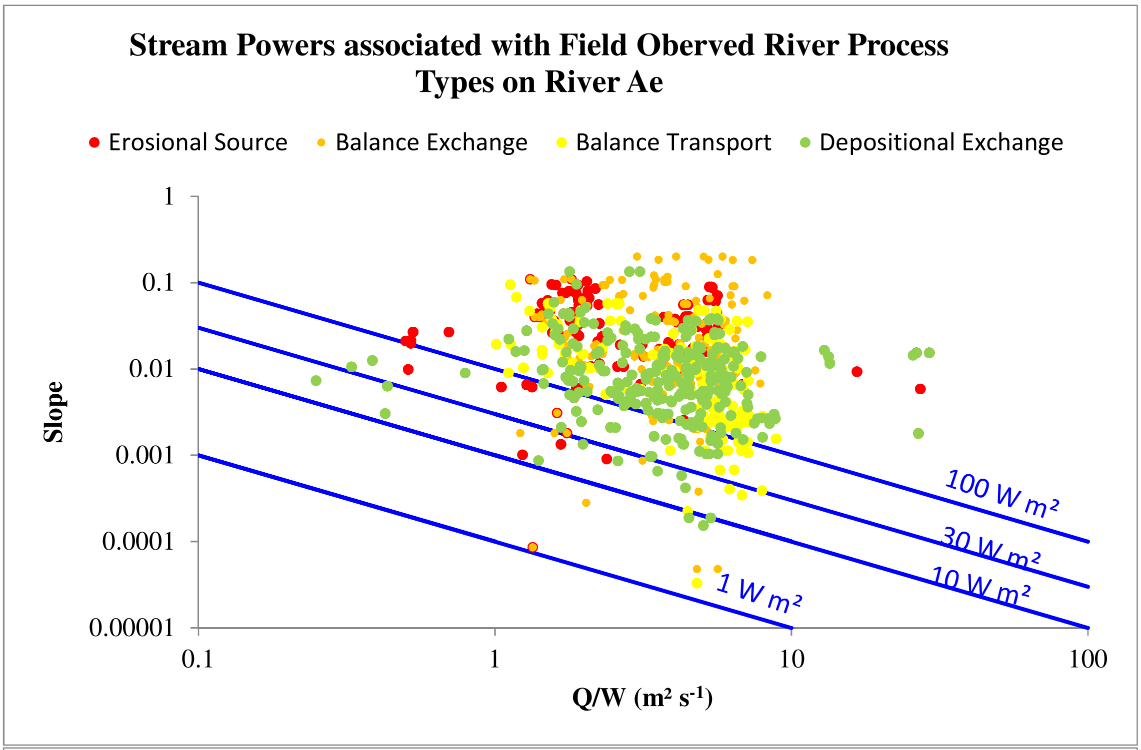


Figure 3.5 Specific stream power plots showing the stream power associated with different channel process type for the River Charnaig and River Farnack. Erosional process types are shown in shades of red, balanced process types in shades of yellow and depositional process types in shades of green to help establish a more simplified picture of channel processes.



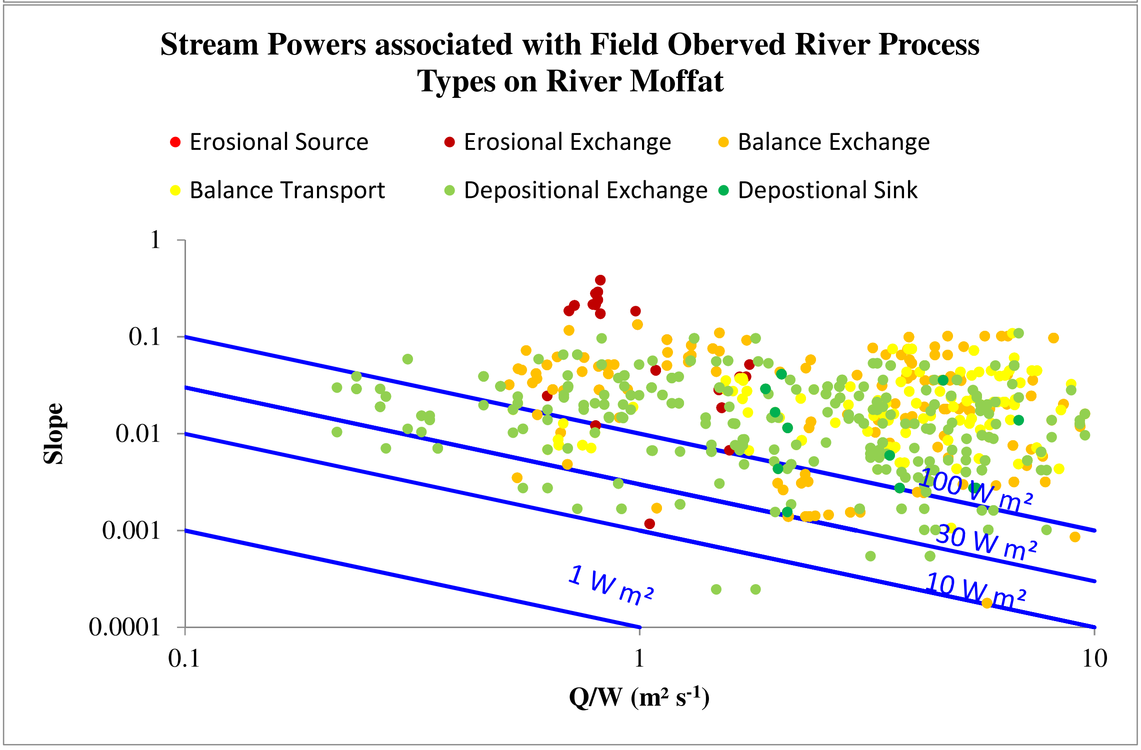


Figure 3.6 Specific stream power plots showing the stream power associated with different channel process type for the River Ae and River Moffat. Erosional processes types are shown in shades of red, balanced process types in shades of yellow and depositional process types in shades of green to help establish a more simplified picture of channel processes.

Table 3.4: Percentage Number of River Reaches within each Stream per Category for each River

Channel Process Type	1	2	3	4	5	6	Total
Watts m^{-2}	River Moffat						
> 100	0.0%	0.4%	30.3%	23.6%	27.2%	1.8%	83.2%
<100	0.0%	0.2%	4.5%	2.1%	5.2%	0.2%	12.1%
<35	0.0%	0.2%	1.6%	0.0%	2.3%	0.0%	4.1%
<10	0.4%	0.0%	0.0%	0.0%	0.2%	0.0%	0.6%
Watts m^{-2}	River Ae						
> 100	0.0%	18.4%	22.1%	17.1%	31.5%	0.0%	89.1%
<100	0.0%	1.2%	1.7%	2.4%	4.1%	0.0%	9.4%
<35	0.0%	0.1%	0.2%	0.2%	0.5%	0.0%	1.0%
<10	0.0%	0.0%	0.2%	0.1%	0.1%	0.0%	0.4%
Watts m^{-2}	River Bervie						
> 100	0.0%	22.4%	41.7%	0.0%	0.0%	0.0%	64.1%
<100	0.0%	3.4%	14.1%	1.0%	9.0%	0.0%	27.6%
<35	0.0%	0.2%	4.9%	0.0%	0.0%	0.0%	5.1%
<10	0.0%	0.7%	2.4%	0.0%	0.0%	0.0%	3.2%
Watts m^{-2}	River Isla						
> 100	5.4%	14.2%	14.8%	9.1%	12.4%	6.4%	62.3%
<100	0.1%	2.9%	6.8%	4.6%	9.5%	1.8%	25.7%
<35	0.1%	0.1%	1.9%	1.6%	1.7%	0.3%	5.8%
<10	0.0%	0.2%	1.9%	1.1%	2.6%	0.3%	6.1%
Watts m^{-2}	River Farnack						
> 100	1.0%	23.4%	5.6%	1.3%	8.9%	1.3%	41.4%
<100	0.0%	10.2%	8.6%	4.9%	6.9%	1.6%	32.2%
<35	0.0%	1.6%	1.6%	6.9%	3.9%	0.7%	14.8%
<10	0.0%	0.0%	1.0%	9.5%	1.0%	0.0%	11.5%
Watts m^{-2}	River Charnaig						
> 100	0.6%	31.0%	2.1%	20.4%	8.8%	5.9%	68.7%
<100	0.0%	4.1%	1.2%	3.8%	10.0%	4.1%	23.3%
<35	0.0%	0.6%	0.0%	0.9%	1.8%	1.5%	4.7%
<10	0.0%	0.3%	0.0%	0.3%	1.8%	0.9%	3.2%
Watts m^{-2}	All Rivers						
> 100	1.1%	15.3%	21.7%	14.9%	21.7%	2.0%	76.8%
<100	0.0%	2.2%	4.6%	2.9%	6.3%	0.8%	16.7%
<35	0.0%	0.3%	1.3%	0.8%	1.3%	0.2%	3.9%
<10	0.1%	0.1%	0.7%	0.8%	0.7%	0.1%	2.6%

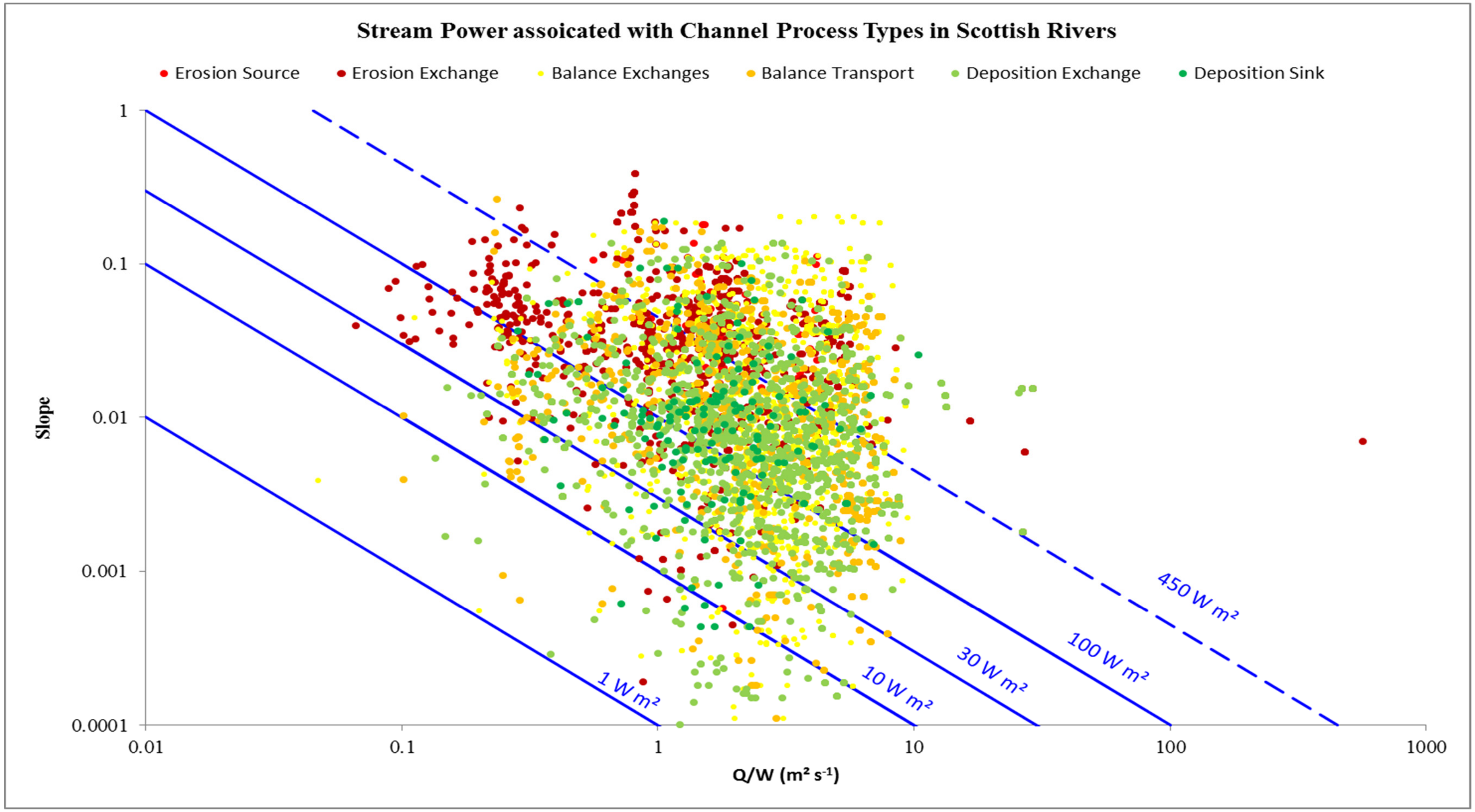


Figure 3.7 Specific stream power plot showing the stream powers associated with six different channel process types (erosional source, erosional exchange, balanced exchange, balanced transport, depositional exchange, depositional sink) for six river catchments across Scotland (Ae, Bervie, Charnaig, Farnack, Isla, Moffat). Erosion dominant processes types are shown in shades of red, balanced process types in shades of yellow, and depositional dominant process types in shades of green to help establish a more simplified picture of channel processes

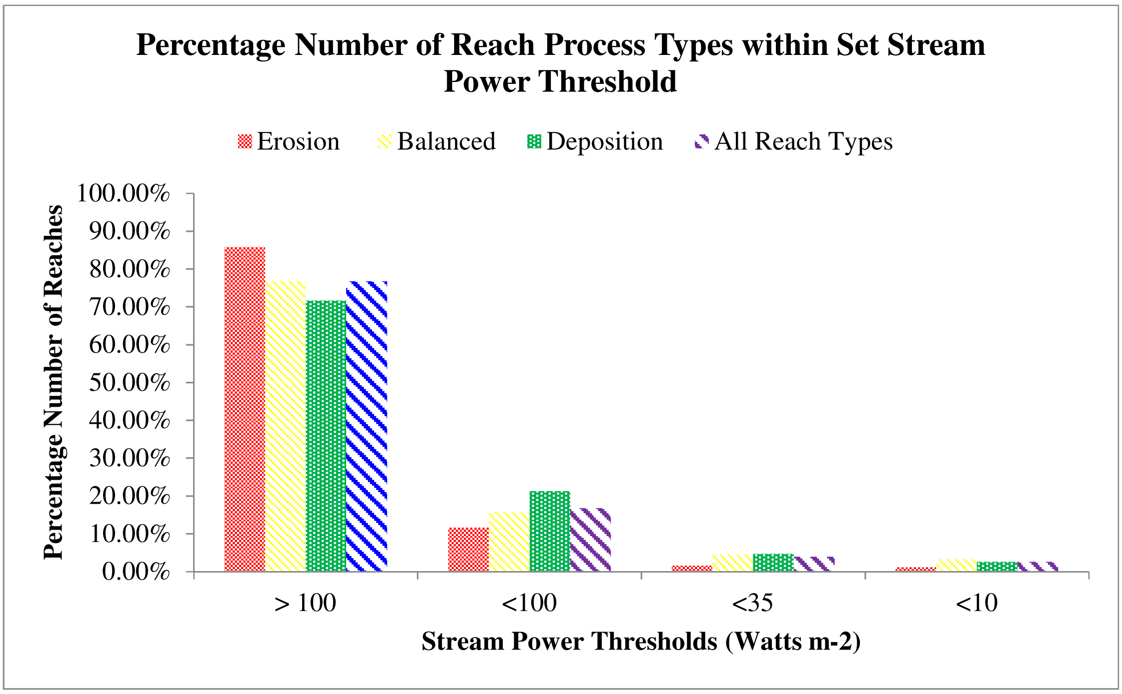


Figure 3.8: The percentage number of reaches observed in the field as either erosion, balanced and deposition dominated reaches, and then all reaches types combined which fall within each of the stream power thresholds defined by Brookes (1987a, b).

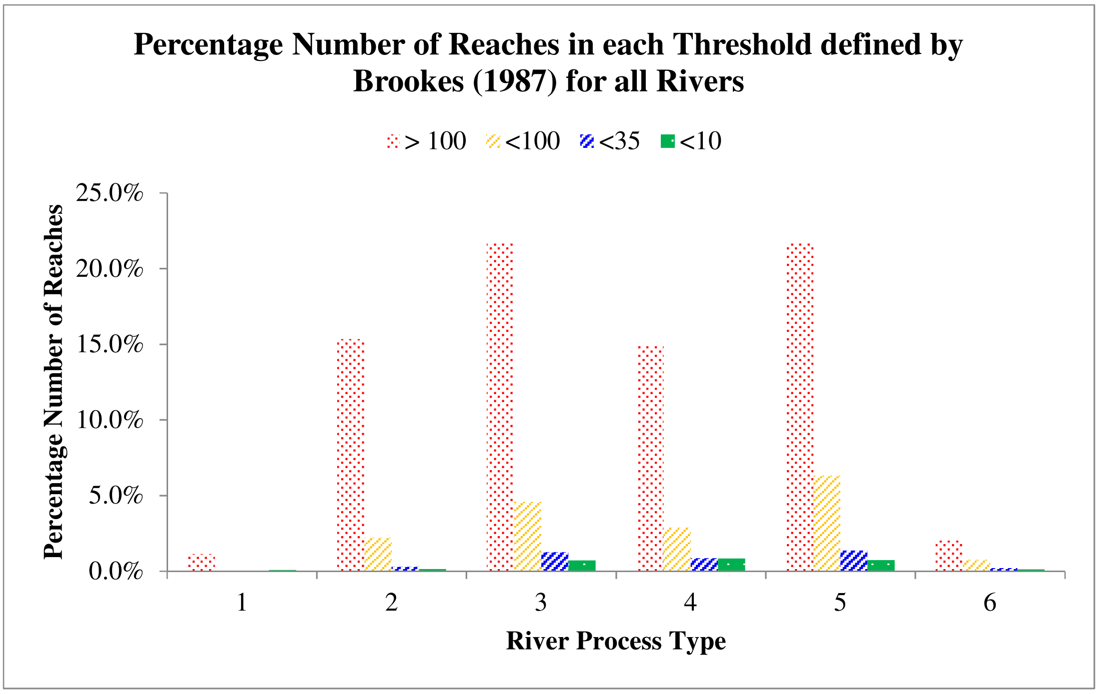


Figure 3.9 The percentage of each channel process type (1. Erosional source, 2. Erosional exchange, 3. Balanced exchange, 4. Balance transport, 5. Depositional exchange, 6. Depositional sink) observed in the field found within each of the stream power thresholds defined by Brookes (1987a, b).

3.3.2 Establishing Stream Power Thresholds for Scotland

A box plot (Figure 3.10) was constructed to assess the variation within each channel process type and the difference between each process type. The box plots show the lower, median and higher quartile for each channel process type. The whiskers at the end of the boxes show the range within the data and outliers which are situated beyond the whiskers are shown by a '⁎'. The two extreme end groups of depositional sink and erosional source reaches have the smallest boxes suggesting a closer agreement of the stream powers within these groups. In the other groups however there appears to be a much larger spread in the stream powers that occur within these reaches, and considerable overlap of the interquartile ranges between the different process types. This meant it was extremely difficult to set thresholds to predict six different channel types, and consequently to simplify a very complex system to screen for channel adjustment.

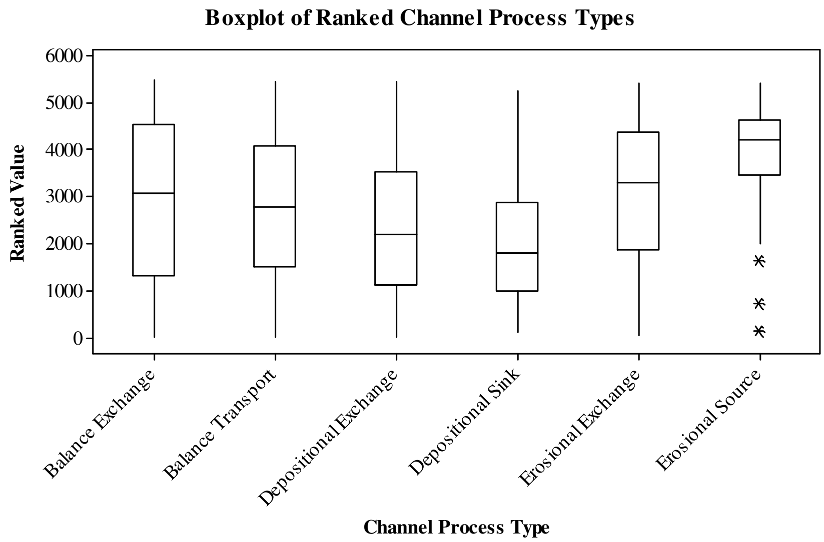


Figure 3.10: Box plot demonstrating the spread of stream power values within each channel process type.

A Kruskal-Wallis statistical test was applied to investigate whether differences in stream power for channel process types were statistically significant. Results showed that there was a significant difference in the stream powers between different river process types (H=257, 5 d.f., **P**=<0.00001). However, post-hoc testing showed there was no statistically significant difference between depositional sink and depositional exchange reaches, and no statistical difference between balanced exchange reaches and erosion exchange reaches. The depositional sink and depositional exchange reaches were therefore joined to create a 'deposition' channel process type, and the balanced exchange and erosion exchange reaches joined to create an 'exchange' process reach type. This created four different channel process types which were: erosional source, exchange, balanced transport and deposition. A box plot (Figure 3.11) of the new channel process groupings was constructed. The box plot showed a considerable overlap of the interquartile ranges between balanced transport (transport) reaches and 'exchange' reaches, but minimal overlap between erosion (erosional source) reaches and deposition process types. Exchange and transport reach types showed considerable overlap with erosion and deposition reaches. This suggests that although it is potentially possible to define a threshold between highly erosional reaches and depositional reaches, it is extremely difficult to define a threshold between deposition dominant reaches and exchange or balanced reaches, and between erosional dominant reaches and exchange and balanced reaches. As a result, no clear thresholds could be developed to discriminate between the different channel process types. Kruskal-Wallis testing was repeated on the four new channel process groups and showed that there was a statistically significant difference (H=257, 3 d.f., **P**=<0.00001). Post-hoc testing confirmed that all groups were statistically different from each other.

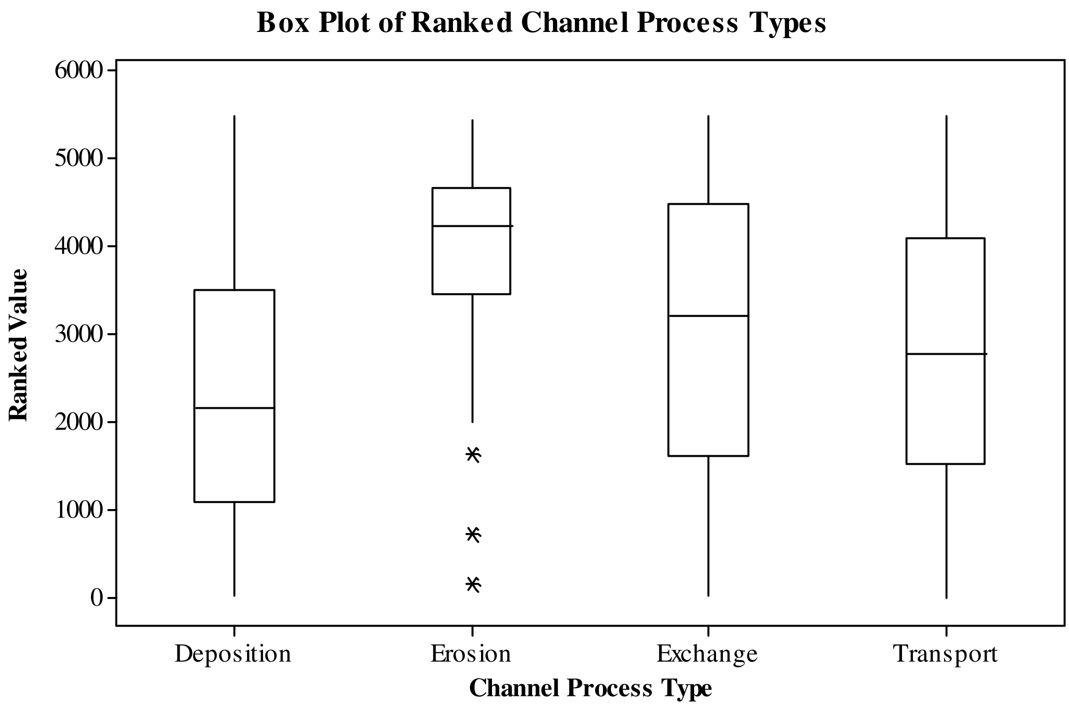


Figure 3.11: Box plot demonstrating the spread of stream power values within the new channel process types: deposition (depositional sink and exchange), erosion (erosional source), exchange (balanced transport and erosional exchange) and transport (balanced transport).

Balanced or exchange reaches in rivers, i.e. those in which sediment erosion is roughly matched by sediment deposition, can in general be viewed as fairly stable; thus for river managers the main concern is predicting which reaches will deposit sediment potentially leading to flood risk, or areas where high erosion could occur and undermine structures. As a result, all balanced or exchange reaches (erosional exchange, balanced exchange, balanced transport and depositional exchange) which have the highest amount of variability in stream power and also potentially could be considered transitional reaches between erosion and deposition were removed, and only the reaches which were at the extreme ends of the original six channel process types, namely erosional source and depositional sink, were considered. Channels with stream power located in the 'gap' between the two process types will be classed as 'exchange' reaches. The aim of this approach is to create thresholds that increase the ability to identify depositional and erosional reaches where there is an increased risk of a channel management problems occurring. However, by having an exchange group it is recognised that there is no strict boundary between deposition and erosion as generally all reaches are in state of exchanging material, while highlighting reaches where deposition and erosion are dominant to the extent that it may cause management problems. The box plot (Figure 3.12) of depositional sink and erosional source reaches showed clear thresholds between the two channel types, with a Q3 value for the depositional sink reach of 314 Watts m^{-2} and Q1 value of 463 Watts m^{-2} for the erosional source reaches.

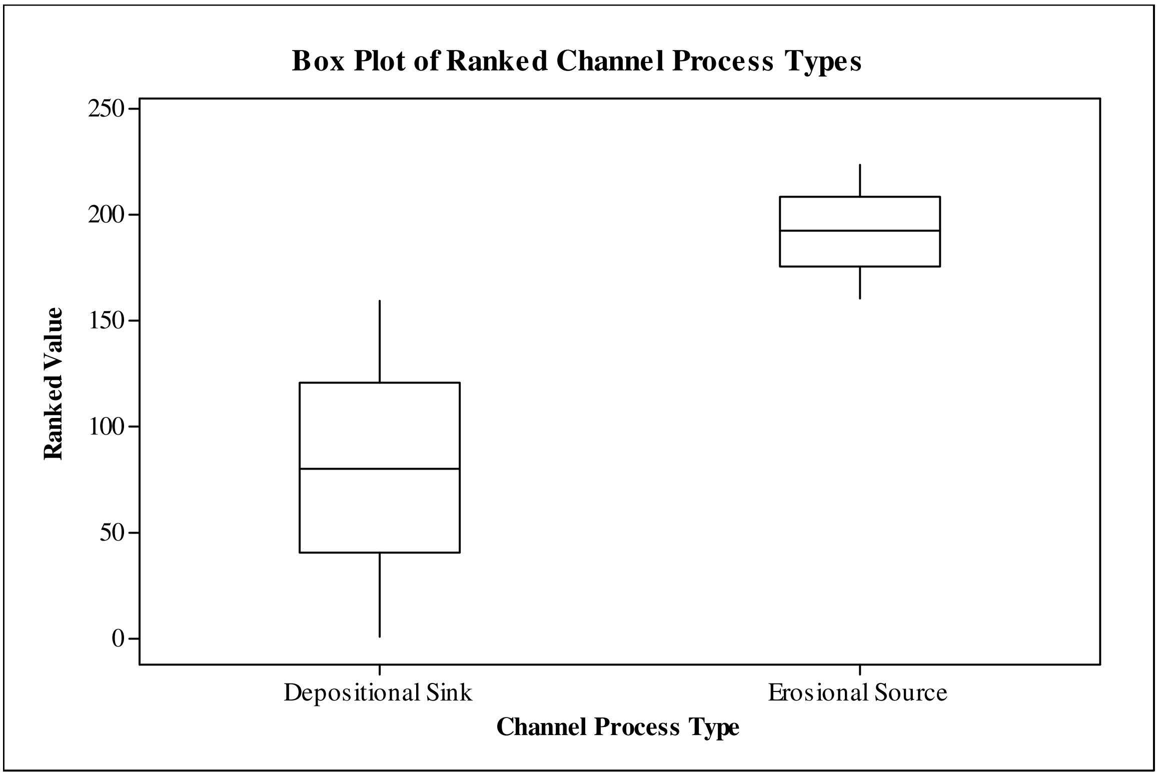


Figure 3.12: Box plot demonstrating the spread of stream power values within the deposition sink and erosional source channel process types.

A threshold stream power of 315 Watts m^{-2} was set with the result that 75% of all depositional reaches fall below this value, meaning the probability of a channel reach below this threshold undergoing deposition processes is high. For erosional reaches a stream power threshold of 465 Watts m^{-2} was set as 75% of erosional stream power values were above this threshold. Thus the probability of a channel reach above this threshold undergoing erosional processes is higher. Stream powers between these thresholds (315 to 465 Watts m^{-2}) would therefore be assumed to be operating some sort of sediment exchange, where depositional and erosional processes within the reach are more balanced. To test the accuracy of these thresholds the six original channel process types were simplified into three groups: erosion (erosional source, erosional exchange and balance exchange), exchange (balanced transport) and deposition (depositional source and sink). The balance exchange channel process type was grouped within the erosional category as no statistical difference from the erosional exchange category was found. Also, the average stream power of the balanced exchange reaches was higher and showed greater similarly to the erosional exchange category than to the balanced transport process type. When these thresholds (Table 3.5) were used to predict channel process types they were found to correctly classify 45% of channel reaches. If the Brookes (1987a, b) thresholds are used to predict channel process types, using the assumption that reaches with specific stream powers < 10 Watts m^{-2} will experience change channel through sedimentation, reaches with stream powers over 35 Watts m^{-2} will experience channel change through erosion, and anything between 10 and 35 Watts m^{-2} is an 'exchange' reach then 44% of channel process in the upland Scottish rivers studied here were correctly classified.

Table 3.5 Thresholds and Threshold Accuracy for Different Channel Process Type Groupings

	Study Thresholds	Brookes (1987a, b) Thresholds
Erosion	>465	>35
Exchange	315 - 465	10 - 35
Deposition	<315	<10
Percentage Accuracy	45.28	44.79

To develop a simple threshold to distinguish between high and low energy river reaches the erosional exchange reach was removed from erosional category because the earlier Kruskal-Wallis test suggested reaches of this type were statistically more similar to the balanced exchange reaches. The depositional reaches (depositional exchange and sink) were still grouped together as the earlier Kruskal-Wallis showed there was no statistically significant difference between the two groups. Interquartile ranges between these two groups did not overlap (Figure 3.13) allowing a clear threshold to be established between high energy (erosional) streams and low energy (depositional) streams of 470 Watts m^{-2}. To test the accuracy of this simplified threshold the higher energy reach process types of erosional source, erosional exchange and balanced exchange were all classed as erosional or 'high energy' reaches and the lower energy reaches of balanced transport, depositional exchange and depositional sink were classed as depositional reaches or 'low energy' reaches. By simplifying the thresholds to predict between high and low energy streams the accuracy of correctly distinguishing between channel process types improved to 58%. When a threshold of 35 Watts m^{-2} was used to distinguish between erosional higher energy reaches and depositional lower energy reaches, which is closer to that suggested by Brookes (1987b), the accuracy of predicting the correct channel process type improved to 48%. If a threshold of 100 Watts m^{-2} was used, then accuracy improved to 51%.

3.3.3 Predicting the Sensitivity of Scottish River Channels to Adjustment

The sensitivity of Scottish river channel reaches to change type under climate change was investigated using the different threshold values outlined in this study. When the thresholds for erosional, exchange and depositional reaches were applied, the east of Scotland was found to have the highest number of reaches classified as depositional, while the west had the highest number of reaches classified as erosional

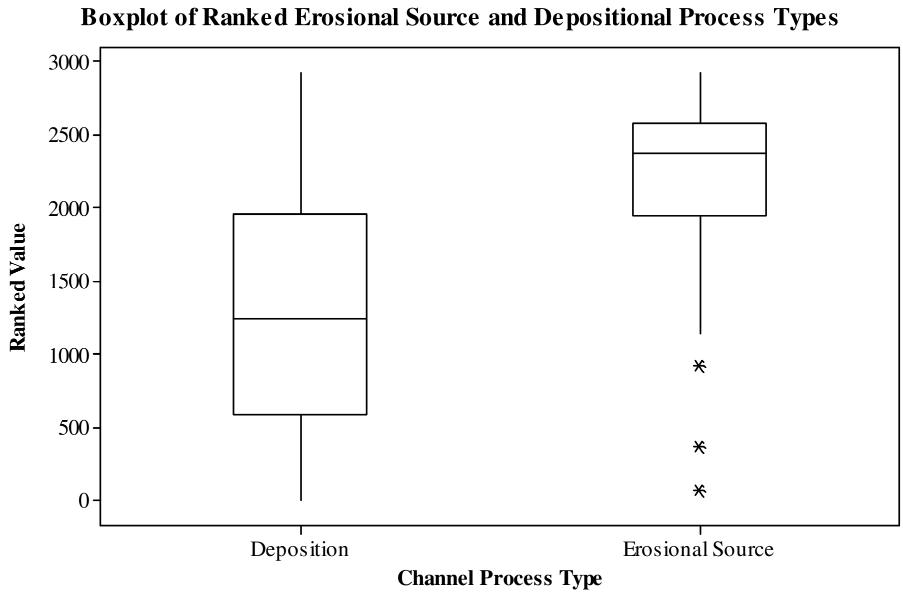


Figure 3.13: Box plot demonstrating the spread of stream power values within the deposition exchange and sink reaches (deposition) and erosional source channel reaches.

The threshold (Figure 3.14 to 3.17) results suggest that the east and north of Scotland would experience the greatest increase in the number of channels reaching erosional stream powers, with 10,237 and 10,254 reaches respectively crossing the stream power threshold of 465 Watts m^{-2} (Table 3.6) In the west of Scotland only 3,178 reaches were found to cross the same threshold. The same pattern can be seen when a stream power of 35 Watts m^{-2} is used as the erosion threshold; however the increase in the number of reaches is smaller at 3,016, 2,423 and 3,767 for the north, west and east respectively. The 35 Watts m^{-2} threshold appears to dampen predictions of a climatic impact on channel reaches, most likely because the number of erosional reaches predicted using this value under current climatic conditions is much higher. When the simple high energy, low energy threshold of 470 Watts m^{-2} was used to investigate the impact of climate change it was found that the location where the highest number of reaches crossed from low to high energy was in the west with 10,773 reaches compared to the 10,215 and 10,202 reaches in the north and east respectively.

Table 3.6 Scottish National Assessment of the Number of Channel Reaches within each Stream Power Thresholds pre- and post-Climate Change

	Study Threshold				Brookes 1987b (Thresholds)				
Specific SP	Scotland	North	West	East	Specific SP	Scotland	North	West	East
>465Watts m^{-2}	115,073	34,722	46,550	33,801	<10 Watts m^{-2}	15,242	5,125	3,688	6,429
315 - 465 Watts m^{-2}	39,606	12,298	12,323	14,985	10 - 35 Watts m^{-2}	26,516	7,879	6,440	12,197
<315 Watts m^{-2}	209,878	65,119	52,879	91,880	> 35 Watts m^{-2}	315,166	99,118	94,008	122,040
>470 Watts m^{-2}	106,390	34,381	38,598	33,411	<35 Watts m^{-2}	41,758	13,004	10,128	18,626
< 470 Watts m^{-2}	250,551	77,758	65,538	107,255	>35 Watts m^{-2}	269,042	23,578	123,424	122,040
>465 Watts m^{-2} CC	138,742	44,959	49,728	44,055	<10 Watts m^{-2} CC	12,106	4,115	2,827	5,164
315 - 465 Watts m^{-2} CC	41,063	12,759	12,035	16,269	10 - 35 Watts m^{-2} CC	20,463	5,890	4,878	9,695
<315 Watts m^{-2} CC	177,136	54,421	42,373	80,342	> 35 Watts m^{-2}	324,372	102,134	96,431	125,807

>470 Watts m^{-2} CC	137,580	44,596	49,371	43,613	<35 Watts m^{-2} CC	32,569	10,005	7,705	14,859
<470 Watts m^{-2} CC	219,361	67,543	54,765	97,053	>35 Watts m^{-2} CC	324,372	102,134	96,431	125,807
Change in the Number of Reaches within each Category with Climate Change									
>465 Watts m^{-2}	23,669	10,237	3,178	10,254	<10 Watts m^{-2}	-3,136	-1,010	-861	-1,265
315 - 465 Watts m^{-2}	1,457	461	-288	1,284	10 - 35 Watts m^{-2}	-6,053	-1,989	-1,562	-2,502
<315 Watts m^{-2}	-32,742	-10,698	-10,506	-11,538	> 35 Watts m^{-2}	9,206	3,016	2,423	3,767
>470 Watts m^{-2}	31,190	10,215	10,773	10,202	<35 Watts m^{-2}	17,327	-2,999	-2,423	-3,767
< 470 Watts m^{-2}	-31,190	-10,215	-10,773	-10,202	>35 Watts m^{-2}	297,856	78,556	-26,993	3,767

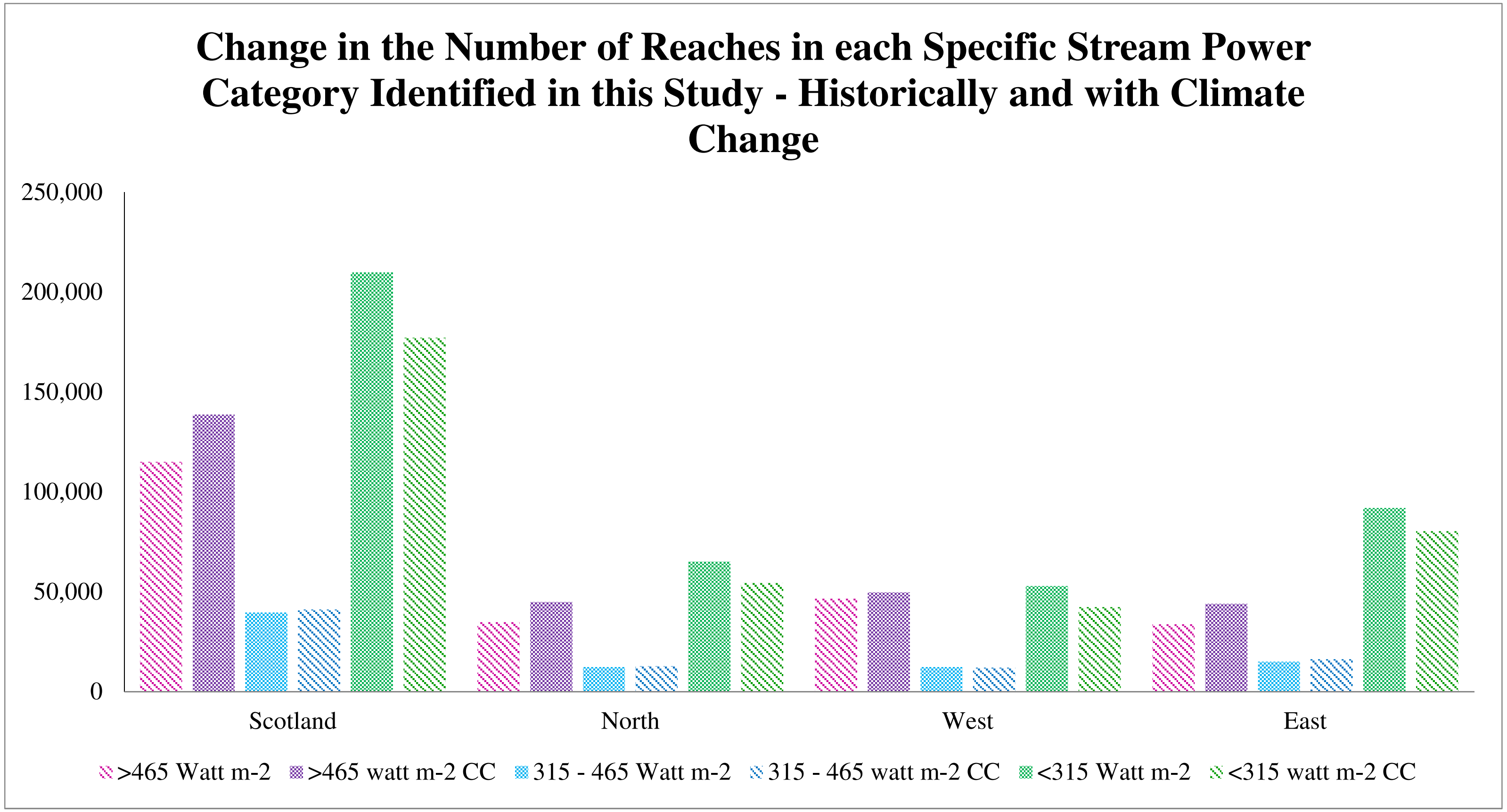


Figure 3.14 The number of channel reaches which fall into the erosional, exchange and depositional channel process type historically and with climate change based on the stream power thresholds outlined in this study. This has been shown for river catchments across the whole of Scotland, the east of Scotland, west of Scotland and north of Scotland.

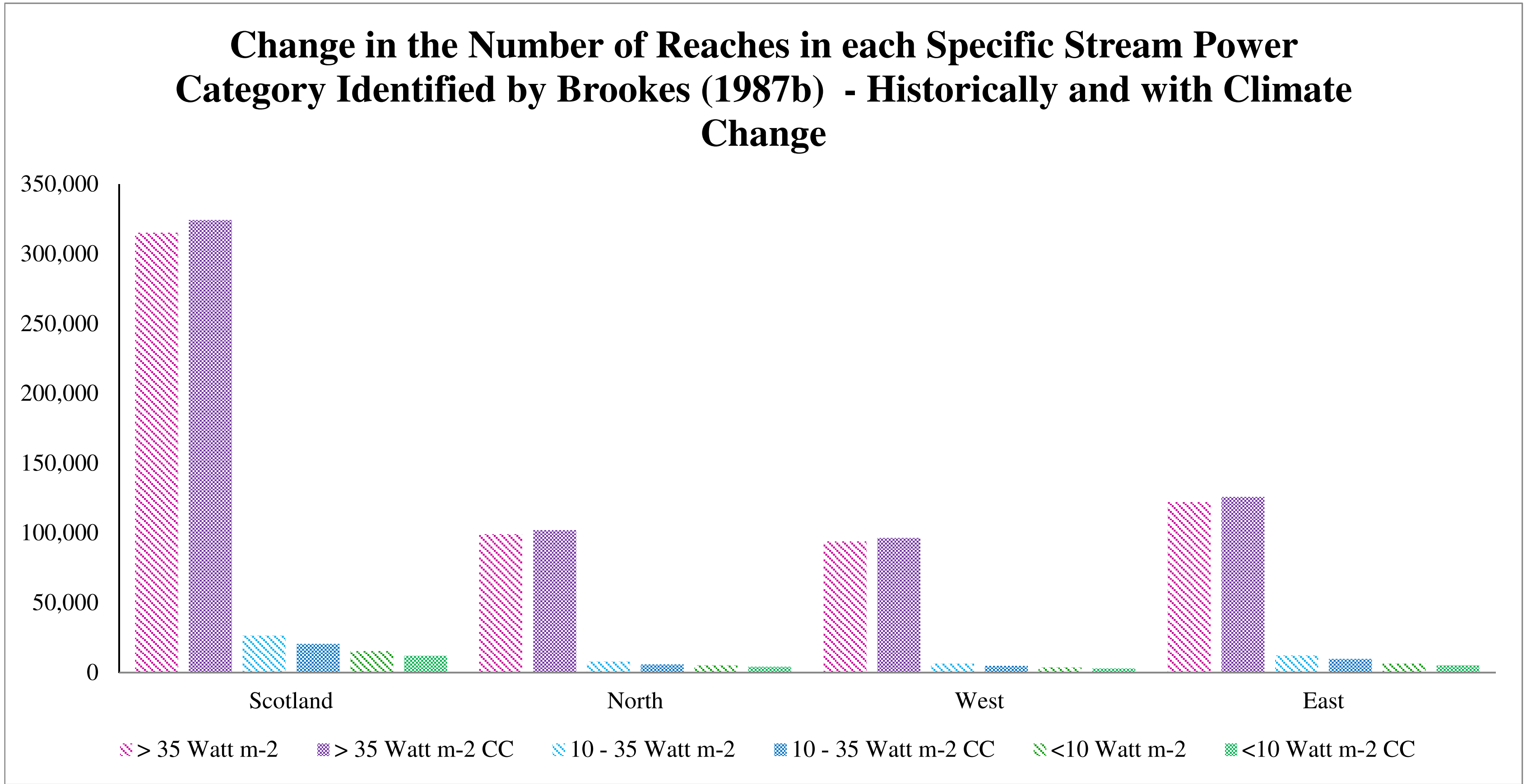


Figure 3.15: The number of channel reaches which fall into the erosional, exchange and depositional channel process type historically and with climate change based on the stream power thresholds outlined by Brookes (1987b). This has been shown for river catchments across the whole of Scotland, the east of Scotland, west of Scotland and north of Scotland.

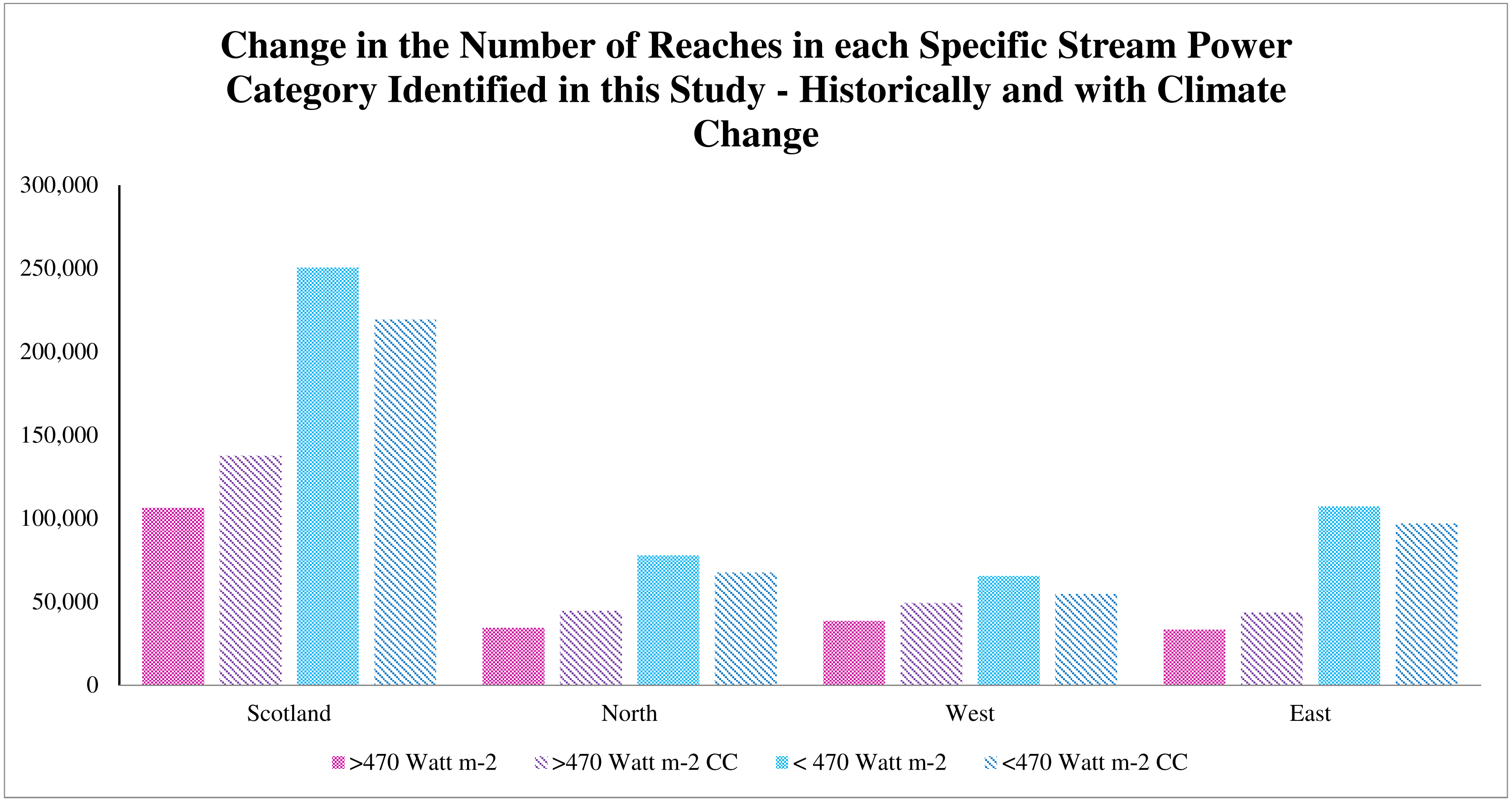


Figure 3.16 The number of channel reaches which fall into the erosional and depositional channel process type historically and with climate change based on the stream power threshold of 470 Watts m^{-2} outlined in this study. This has been shown for river catchments across the whole of Scotland, the east of Scotland, west of Scotland and north of Scotland.

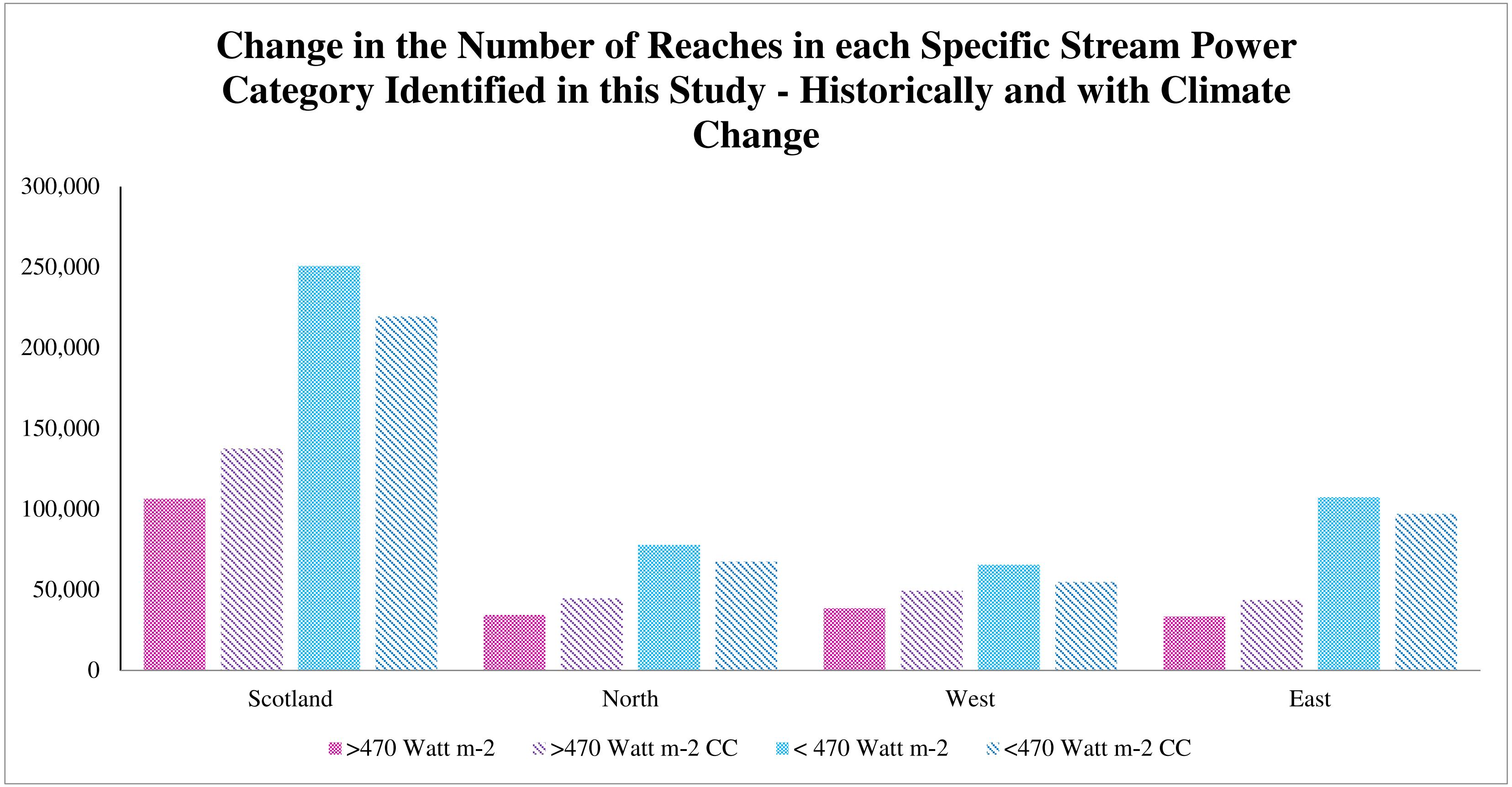


Figure 3.17 The number of channel reaches which fall into the erosional and depositional channel process type historically and with climate change based on the stream power thresholds of 35 Watts m^{-2} outlined by Brookes (1987b). This has been shown for river catchments across the whole of Scotland, the east of Scotland, west of Scotland and north of Scotland.

3.4 DISCUSSION

3.4.1 Stream Power Thresholds

Visually the results suggest that the original stream power thresholds outlined by Brookes for England and Wales in 1987b were too low for the upland landscape of Scotland, with over 75% of all reaches studied having a specific stream power more than 100 Watts m^{-2} and over 90% of reaches having a specific stream power in excess of 35 Watts m^{-2}. This is further highlighted by field observations indicating that only 19% of reaches are considered erosional, increasing to 46% if the balance exchange group is included as erosional. Thus, it could easily be concluded that a threshold of 35 Watts m^{-2} is too low to accurately predict erosional reaches or active reaches within Scottish rivers. To some extent this is not entirely surprising as Brookes (1987b) himself stated that 'streams in markedly different hydrological and sedimentological environments may possess different threshold values'. Furthermore, it has been suggested that as the size of bed material increases from silt to gravel to cobbles the specific stream power associated with channel instability also increases (Thorne et al., 2010). The Brookes' thresholds were developed using highly modified sand channels suggesting that in river will smaller grain sizes and higher levels of modification will adjust more easily and at lower stream powers than more natural gravel bed channels of Scotland. This when looking at potential for a river reach to adjust we need to consider not only the stream power of the reach but grain size and potentially also level of channel modification.

A change in stream power thresholds experienced due to different hydrological and sedimentological environments was well illustrated when Ferguson (1981) compared stream power thresholds developed for braided and meandering rivers in America (Leopold and Wolman, 1957) with rivers in the UK. The stream power threshold, although still present, was 2-3 times higher than found in American rivers. This was attributed to a difference in bed material (Ferguson, 1981). In the same study Ferguson (1981) looked at four channel types within Britain: active meandering, confined meandering, active low sinuosity and inactive channels. Inactive straight or sinuous channels tended to have lower specific stream powers, active low sinuosity high specific stream power and active meandering channel intermediate stream powers (Table 3.7). Ferguson's later, 1987, review of stream power thresholds to distinguish between different channel types discussed the importance of bedload as well as stream power and slope in defining the transition from straight to meandering to braided channels. In essence, the transition from straight to braided is associated with increased bedload transport as well as an increase in slope and stream power. Others (Schumm, 1981), have suggested that the stream power thresholds between different channel patterns vary for bedload, mixed load and suspended-load channels. Earlier work looking at thresholds to predict channel pattern and, in particular, the difference between braided and meandering river channels, found that in general terms braided channels occurred at higher bankfull discharges and slopes (Leopold and Wolman, 1957) in both gravel and sand-bed channels. This was further backed up by later flume-based studies (Ackers and Charlton, 1970; Schumm and Khan, 1972; Edgar, 1984) which suggested that as slope and discharge increased, and therefore stream power increased, channels progress from straight to meandering to braided. These traditional statistical and environmental studies highlighted the potential usefulness of using stream power in distinguishing between channel types and channel activity, as discharge and slope are the two main parameters used to calculate stream power (Ferguson, 1981; Knighton, 1998). However, this theory works on the principle that a high discharge and high slope means there is more power available to erode and move sediment, which although true, also assumes that bedload size and bank strength remain constant which in reality is not the case. For example, a reach could have a lower stream power but smaller pebbles so less energy is required to move the pebbles. When Ferguson (1981) investigated channel pattern thresholds for UK river channels he highlighted the potential need to consider other parameters such as sediment calibre and bank strength when trying to predict channel type. He found that although braided channels in the UK supported the idea of a threshold stream power for channel braiding, it was two to three times higher than the 50 Watts m^{-2} suggested by Leopold and Wolmon (1957), due to the larger gravel or cobble sediment being less mobile than the sandy channels studied by Leopold and Wolmon. When channel activity was reviewed, it was found that stream power in inactive river channels was often low and not powerful enough to erode the channel boundary. Stream power ranged between 1 and 60 Watts m^{-2} with a median value of 15 Watts m^{-2}. However, channels with higher stream powers were also found to be inactive if confined or incised, for example bedrock or tree-lined reaches, highlighting the complexity in predicting channel change and the importance of considering bank strength and erodibility. In contrast, active unconfined meanders had stream power between 5 and 350 Watts m^{-2} with a median value of 30 Watts m^{-2}. Although these median values for active and inactive channels relate well to the thresholds found by Brookes (1987b) for channel activity in river channels in England and Wales, the large range of stream powers and the influence of the channel boundary in active rivers suggests that other factors are important in determining channel shape. Ferguson (1981) highlighted in his work the wide scatter of discharge-slope relationships in straight channels by Leopold and Wolmon (1957); and the postglacial adjustments which have been occurring in the UK, specifically a marked increase in vegetation increasing bank stability and reducing sediment supply and discharge. As a result, his observations do not match the laboratory conditions used to define thresholds in other studies (Ackers and Charlton, 1970; Schumm and Khan, 1972; Edgar, 1984). Other studies (Osterkamp, 1978; Carson, 1984; van den Berg, 1995; Eaton et al., 2010) have stressed the importance of bed material when predicting channel pattern and creating thresholds between differing channel types, while others have stressed the importance of the erodibility of the channel boundary (Schumm, 1963; Bridge, 1993; Raven et al., 2010). Smith (1976) found that riparian vegetation with a five centimetre root and root density of 16-20% was found to increase bank reliance to erosion by 20,000 times. Channel geometry has also been found to be an important factor in the ability of a river to adjust the channel boundary (Knighton, 1998). Shear stress tends to be greatest along the thalweg, meaning that in straighter channels the shear stress tends to be greatest down the middle of the channel, and thus along the channel bed rather than along the channel banks. However, in meandering channels the thalweg tends to sit closer to the outside bend of the channel increasing the shear stress and erosion of the channel banks on the outside bend of the channel (Soar and Throne, 2001). The results therefore highlight the importance of sediment size and the channel boundary in predicting channel activity and channel patterns. Thus using stream power alone to predict channel activity and channel type fails to recognise the importance of channel bedload and sediment supply, which ultimately are two key parameters in the development of channel pattern (Schumm, 1977; Thorne, 1997).

An added difficulty in defining a standardised set of stream power thresholds to determine channel pattern is that discharge, slope, sediment and channel pattern are all defined differently (Ferguson, 1987) in different studies. For example, the threshold between different channel patterns will vary depending on whether mean discharge, bankfull discharge or a return interval discharge is used. Variations in slope occur between laboratory and field studies too. In the field, slope is measured either along the channel or the valley where as in the laboratory flume experiments it is measure in a straight-line. Using a straight-line or valley slope reduces the difference in slope between meandering and braided channels, leading increased difficulty in defining the two channel types

(Ferguson, 1987). Similarly, different researchers characterise channel patterns and processes differently. Brookes (1987a, b) defined channels in terms of recovery through erosion and deposition, Ferguson (1981) used confined, active meandering, active low sinuosity, and inactive unconfined, Leopold and Wolmon (1957) straight, braided, meandering and here channel process types have been used. The differences between channel classification makes it extremely difficult to define a robust and standardised set of stream thresholds for defining channel pattern. The issue being each set of thresholds are defining channels with different forms and processes. When using stream power thresholds to predict channel form it would therefore be advised to ensure that the thresholds being used have been developed using the same measurements of slope, discharge, sediment size (where appropriate) and assumptions on channel pattern.

The limitation of using just specific stream power to predict channel stability, and the importance of bedload in predicting active and in-active channels, was further supported by Stacey and Rutherfurd (2007) when they investigated over 1000 sites in Fairfax County, Virginia. Their work found no clear thresholds between stable and unstable channel reaches, but did conclude that substrate type had a greater influence on channel stability than specific stream power. The importance of considering channel material and sediment supply when predicting channel process types has long been recognised in geomorphology as highlighted by Schumn (1977) when he emphasised water and sediment were the primary independent variables governing channel morphology. When this is considered, a large overlap in stream power of different channel process types, as found in this study, is not surprising. As such, the difficulty of developing clear thresholds between different channel process types should be expected. It is also important to consider that, although Brookes identified a 35 Watts m^{-2} as a threshold to discriminate between stable and unstable channels, this threshold was developed looking at channels which had undergone channelization within England and Wales. These channels are very different from the high energy meandering gravel and cobble bed river found extensively in Scotland. However, Brookes did acknowledge that these thresholds value may vary under different environmental and sedimentological conditions. The fact that these streams were managed is also significant; newly straightened channels have a high hydraulic efficacy and tend to lack vegetational features which would dissipate energy, making it unavailable for erosion and sediment transfer (Thorne et al., 2010).

Other studies, however, have found a good agreement between stream power predicted channel stability and channel process types. Newson et al., (1998) found that specific stream power was the most important variable in predicting channel stability, when he investigated the relationship between channel stability and other geomorphic drivers of channel change such as slope, bank strength, catchment area and sediment supply. The TWINSPAN analysis undertaken to identify the most important parameters when geomorphologically classifying rivers, found that specific stream power explained the highest amount of variation between channel types. Stream power was found to explain 6.2% of the total variance (Newson et al., 1998). The importance of substrate was also highlighted but was found to only marginally improve the ability to predict channel type. This study, however, unlike Bizzi and Lerner, (2015), did not specifically investigate the value of stream power to distinguish between individual channel process types. Bizzi and Lerner, (2015) explored whether total and specific stream power could be used to identify which channel process (erosion, transport or deposition) was dominant within a river reach using two English gravel bed rivers. Unlike in this study, channel confinement was also considered allowing unconfined and confined channels to be considered separately, and different stream power thresholds were developed for each group. The study found that in unconfined channels a specific stream power of 34 Watts m^{-2} was required before erosional features would form, and therefore concluded that this value acted as a stability threshold. This threshold value compares well with the Brookes (1987a,b) threshold of 35 Watts m^{-2} and Orr et al.'s (2008) threshold of 30 Watts m^{-2} for a change between deposition and erosion dominated reaches. In this study, with 18 and 55 out 160 depositional sink reaches and 187 and 480 depositional exchange reaches having a specific stream power of less than 35 and 100 Watts m^{-2} respectively, a threshold of 35 Watts m^{-2} would be too low to accurately define between erosion and deposition dominated reaches, as it would mean the majority of observed deposition dominant reaches would be classed as erosion dominated reaches.

The importance of sediment supply, sediment calibre and bank strength in predicting channel type assists in explaining the wide range of stream powers which are found across the original six channel process types identified in this study; and thus the difficulty in defining clear cut thresholds. As these channel process types occur along a continuum, meaning each type merges from one type into another, the boundaries or thresholds between each type are fuzzy and complex and not completely separate (Knighton and Nanson, 1993; Bledsoe and Watson, 2001) . A number of others reduce this complexity and fuzziness by looking at a simple threshold between stable and unstable or erosion dominant and deposition dominant (Parker, 1978; Brookes, 1987a, b). By doing this they do not take into the account that fuzzy boundary where a reach is on, or close to, a threshold between stable and unstable – i.e. is transport dominant rather the erosion or deposition dominated. This suggests that stream power is a useful method for looking at the extremes but less useful in predicting intermediate conditions and may explain why in this study the channel process types had to be simplified in order to find a meaningful threshold values and the difficulty in distinguishing between the six different channel process types. In this study an intermediate category has been included in an attempt to try and classify some of the fuzziness between erosional and depositional process types and ensure that an attempt has been made to classify channels which are in states of flux, where transport processes dominate.

The findings from this study suggest that the stream power thresholds developed by Brookes (1987a, b) are too low to accurately represent the upland landscapes of Scotland. However, when the accuracy of the thresholds of 315 and 465 Watts m^{-2} defined using the data from this study were compared to the thresholds of 10 and 35 Watts m^{-2} suggested by Brookes for managed channels in England and Wales there was less than a 1% difference in the level of accuracy between the two threshold groups. Over the whole of Scotland this would be the difference in accurately defining 5569 reaches. Regardless of difference in accuracy only being 1% for study reaches, when the patterns of erosion and deposition were reviewed over Scotland as a whole, it still appears on examination that Brookes's thresholds are too low for the Scottish landscape. Under Brookes's thresholds 88% of all river reaches across Scotland are considered to be erosion dominated reaches compared to 32% based on the thresholds developed in this study. In the field 19% of reaches observed were categorised as erosional. A value of 88% would appear too high when you consider that only 46% of study reaches were considered to be erosion dominant, and only 42% of reaches across Scotland were considered erosional, when the ST:REAM model (Parker et al., 2015) was applied to the whole of Scotland by SEPA (2013). When SEPA further investigated erosion dominated reaches for different regions across Scotland the percentage number of erosional reaches varied from 34% to 39%; still less than half of that suggested using the Brookes thresholds. A combination of factors could explain this, three are suggested here: (i) the high-energy upland catchments of Scotland tend to transport gravel which requires more energy to move, (ii) many channels banks are vegetated, meaning that the channel boundary is highly resistant to erosion, (iii) bed sediment is typically densely packed meaning more energy is required to mobilise the gravel bed (Pender et al., 1998). This means, despite the river reaches having energy to erode and do work, the rivers require a lot more energy to erode and move sediment than in low land alluvium channels. Additionally, the managed channels being surveyed by Brookes (1987b) were straighten channels and most likely lacking in vegetation features, meaning that the hydraulic efficacy of those channel would be higher than the wandering vegetated river channels of Scotland, where the planform and riparian vegetation dissipates energy making it unavailable for erosion and sediment transfer (Thorne et al., 2010). The percentage of depositional reaches were 4% and 66% respectively for the Brookes and study thresholds. This compares to 36% for the whole of Scotland, and a range of 34% to 39% for the different regions across Scotland from the SEPA ST:REAM model. Reflecting on these results, they would suggest that the threshold for deposition reaches developed in this study is possibly too high and needs further examination, but that the Brookes thresholds on the whole are too low to show a representative pattern of channel erosional and dispositional reaches across Scotland. Still, if either of these thresholds were used to predict channel processes on a national scale there is a less than 50% chance that model will accurately predict the channel process type for a 50m channel reach. This further highlights the need to consider bedload and channel boundary material when trying to predict channel dynamics.

When the one threshold (i.e. all reaches with stream power below 470 Watts m^{-2} are deposition and all reaches above 470 Watts m^{-2} are erosion) was used to define between erosion dominant and deposition dominant reaches 58% of channel reaches were correctly classified. Using a stream power threshold of 470 Watts m^{-2} to identify between erosion dominant and deposition dominant changes was found to be 10% more accurate for channels in this study than the threshold of 35 Watts m^{-2} suggest in literature

(Brookes, 1987b; Orr et al., 2008; Bizzi and Lerner, 2015;). This means using a threshold of 470 Watts m^{-2} in Scottish upland catchments rather than 35 Watts m^{-2} for the whole of Scotland would potentially result in 55,690 more reaches being accurately categorised. This suggests that when looking at channel stability using a simple threshold whereby a single stream power value is used to distinguish between erosion and deposition is a potentially more effective tool for looking at changes in channel processes than one that tries to identify a transition zone. This is most likely due to the complexity of the fluvial system.

Based on the threshold developed in this study, when the impact of climate change is considered, the increase in the number of erosion dominated reaches during a Q_{MED} flood would be significantly lower for the west of Scotland compared to the east and north, with the increase in the number of reaches being 3178, 10,254 and 10,237 respectively. The decrease in the number of depositional reaches with climate change was more consistent with decreases of 10,698, 10,506 and 11,538 for the north, west and east of Scotland respectively. These findings suggest that in general Scottish rivers are fairly resilient to the predicted threat of increased flood flows. Previous work (Werritty and Leys, 2001) also suggest that Scottish upland rivers were more 'robust' to environmental change due to Scotland's glacial legacy, wide valley floors and land use. The east of Scotland catchments have the smallest percentage change in reach typology at 8.2%, but due to the majority of Scotland's agriculture and urban populations being located in this region it would be advisable to investigate further to ensure the any potential effect to society can be managed. The percentage change for Scottish rivers in the north and west is 9.5% and 9.4% respectively.

One final thing to consider is that the stream power values used in this study are based on modelled discharge values for Q_{MED} flood, which has been assumed to representative of bankfull flow, but when Brookes developed his original values it was based on field survey data. This means that there is potentially uncertainty in the accuracy of the discharge values; and also the assumption that discharge will increase linearly as the river flows downstream may not be valid. Although, in the future power regression between Q_{MED} and Shreve's index can be used to account for the non-linear relations than occur between flow and distance downstream (Knighton, 1999; Bizzi and Lerner, 2015). Despite the discrepancy between model and field discharge values it is still useful to look at the difference in stream power thresholds in this manner. This is because it is now common practice to use spatial data to develop stream power values for river reaches, rather than carrying out time-consuming field surveys. Therefore, developing thresholds using spatial data ensures a greater accuracy in predicting channel process type using stream power values based on spatial data. Also, even if field survey discharges were found to be closer to the thresholds developed by Brookes (1987b), this study has shown that using these thresholds on spatial derived data will not lead to representative results. Other uncertainties with this approach to calculating stream power could come from channel slope calculation and channel width. However, with future improvements in digital evaluation models and spatial data it likely that through time the level of uncertainty in calculating stream power using spatial data will decrease.

3.4.2 Management and Future Work

Using stream power as a means of accurately predicting channel process types, like those described here, is extremely difficult due to the complex process involved in channel development. Furthermore, stream power is a measure of driving forces and therefore does not take into account resisting forces such as bedload and channel boundary strength. Therefore, ideally to predict more accurately how a river will respond to changes in discharge and stream power, parameters such as sediment size, sediment input and availability, and bank strength would need to be considered. However, using a stream power map such as the Digital Stream Power River Network develop by SEPA and models such ST:REAM, to highlight areas of changing stream power values can still be a useful tool in predicting areas of potential channel instability. If sudden changes in stream power values are present along a stretch of river it could be assumed that there is the potential for a marked change in channel behaviour and channel geomorphology in these locations. The ability to be able to do this gives river managers a useful screening tool to assess potential areas of instability and change before undertaking more detailed and time consuming field work and modelling. Vocal Ferencevic and Ashmore, (2012) demonstrate this when developing a digital stream power map for an entire river catchment to predict channel behaviour in Highland Creek near Toronto, Canada, to aid river management decisions and ensure river rehabilitation efforts did not negatively impact important infrastructure. The stream power map was able to accurately predict the reaches that underwent the most geomorphic change during a 1:100 year flood and proved extremely useful in identifying key areas where more detailed field surveys and modelling should be focused. In addition, if the concept of scale is considered, it can be reasoned that although using very generalised stream power thresholds on a reach by reach basis to investigate channel stability and morphology can lead to poor result accuracy, at a coarser national-scale resolution it can provide good general overview of channel stability and identify potential locations for change, particularly with climatic change. For river managers to have some gauge of how sensitive rivers are to change, and the broad areas where this is more likely to occur, will allow for better planning to ensure money and time is invested in the right areas in the future. The ability to use stream power thresholds could be improved if more research was done looking at how these thresholds vary with bedload type and/or channel morphology. This would mean that if you were looking at an upland gravel-bed river you would use a different set of thresholds to a lowland gravel-bed river, or a lowland river with a sandy bed. Although, this still would not be as accurate as a sediment transfer model it would provide a more accurate screening tool and reduce some of the uncertainty of using a blanket set of thresholds for all river types (which tends to be the case at present). However, due to the complexity of the fluvial system, and complex interactions between slope, discharge, sediment and bank strength stream power thresholds should be used with caution, and ideally as part of the initial screening process when trying to identify solutions to river management problems.

3.5 CONCLUSION

The data from this study suggest that for Scottish rivers the thresholds outlined for by Brookes, (1987b) for managed channelised reaches in England and Wales are possibly too low for predicting channel deposition and erosion in the high energy upland rivers of Scotland. However, there was only a 1% increase in the accuracy of predicting channel process type using the thresholds developed here compared to those outlined by Brookes (1987b). On further investigation and comparison with others it would appear that the Brookes (1987b) thresholds overestimates the number of erosion reaches within a catchment and underestimates the number of exchange and depositional reaches. However, if a simple erosion dominant, deposition dominant threshold is used of 465 Watts m^{-2} instead of 35 Watts m^{-2}, the number of reaches correctly classified increases by 10%. Ultimately, although stream power provides a quick and easy way to investigate differences in a channel's ability to erode and transport sediment, its ability to predict more in-depth channel processes is limited as it fails to consider bank material and channel bedload size, two parameters which have a distinct influence on channel morphology and a river's ability to adjust. Thus it would useful to add a bedload element in order to try and more accuracy predict channel processes, and adjust on a national scale. Despite this, the simplicity of using stream power as an initial screening tool should not be disregarded. As long as the appropriate stream power thresholds for the type of channel under investigation are applied, it does provide river managers with a simple and easy way to screen channels for areas of potential change, and highlight general patterns in channel process over large spatial scales. To ensure appropriate stream power thresholds are applied and used by river managers it is recommended that the way in which these thresholds potentially vary between different river systems is investigated. Until then the use of the Brookes thresholds should be restricted to the channels they have been proven to be representative of.

3.6 SUMMARY

- The stream power thresholds set out by Brookes are too low for the high energy upland rivers of Scotland.
- Due to the complexity of the fluvial system it is difficult to use one set of thresholds to define the dominant processes within a river reach
- The development of stream power thresholds for different river systems e.g. upland gravel bed rivers, alluvium channels, managed channels would provide more accuracy and better screening at the reach scale.
- The use of appropriate stream power thresholds is still a useful initial screening tool to look for patterns or sudden changes in channel process at larger scales, although should be used with caution at the reach scale where more detailed modelling would be advised.

CHAPTER 4

Investigating Changes in the Rate of Bedload Transport with Climate Change

4.1 INTRODUCTION

Rivers are constant conveyor belts of sediment. The erosion, movement and redistribution of sediment around the globe are important drivers in landscape development as a whole, but they are also key factors in the geomorphology of river channels (Walling, 2009). Understanding the sediment regime of a river channel can provide managers with an insight into the hydrology of the river, water quality, geochemical cycling, as well as the ecosystem services provided by the channel (Walling, 2009). It is important, therefore, that river managers can predict when and where changes in the sediment regime could occur. As climate change is expected to increase not only the magnitude of floods, but also the frequency at which they occur, it is important that river managers can predict and understand the changes that this could bring to the sediment regime of the river. This not only applies to the physical river process but also the potential socio-economic impacts such as flooding, reservoir sedimentation, loss of agricultural land and the deterioration of infrastructure. The sediment system of a river can essentially be broken down into three parts. These are: areas of sediment supply, sediment transport and sediment storage (Sear et al., 1995). An understanding of these three components of the sediment system is essential in understanding how river systems evolve and function, and for understanding the direct and indirect impact on channel stability resulting from different management decisions (Hooke, 2003). The supply of sediment to a river from the surrounding catchment is often dependent on the coupling, or connectivity, between the valley sides and the river channel (Harvey, 2002). In well-coupled channels changes in sediment supply are transmitted downstream throughout the river system, whereas in poorly-coupled systems the change within the river system is conveyed more locally within the channel (Harvey, 2002, 2001). Sediment transport involves the movement and distribution of sediment throughout the system. This is usually from areas of sediment supply to areas of sediment storage. The sediment load of the river is composed of three main components: dissolved load (which carries ionic solutes), suspended load (which carries silt and clay particles) and bedload (which carries sediments coarser than fine sands) (Sear, 1996). Channel bedload is of greatest interest for this thesis because has it has the biggest impact on channel morphology and reach-scale processes. Before sediment can be transported downstream the river must have enough power to move the sediment along the river channel. Therefore it has been found that bedload transport tends to occur in waves or pulses (Reid and Frostick, 1986; Reid et al., 1985), i.e. it occurs periodically when the river has enough power to transport the bedload material. As the sediment is transported downstream over time in waves it is temporarily stored within the channel system, often within channel bars, or over longer time periods in the floodplain, before the river has enough power to transport it further downstream (Venditti et al., 2010a, b). The distribution of sediment within a reach has a significant part to play in determining not only channel morphology but also channel stability, and is controlled by the hydrologic regime of the river, and the resistance of the channel boundary to adjustment (Sear, 1996; Lane and Richards, 1997; Thorne, 1999). In addition, the sediment regime of the river can have a significant impact on flooding, as was demonstrated by Lane et al., (2007) with his study looking at sediment delivery on the River Wharfe, which showed floodplain inundation for a 1:2 year flood increased by 7.1% due to in-channel sedimentation. Therefore, to ensure sustainable and effective flood mitigation practices, and successful river restoration projects, knowledge of the sediment regime of the river is imperative (Newson, 1993; Sear, 1996).

Historically, river and flood defence management schemes have focused on inflexible engineering practices which have tended to ignore the natural dynamics of the river channels, and the importance of bedload transfer within the fluvial system (Werrity, 2006). Although these hard engineering practices, such as channel-straightening, channelization and dredging, are often effective in fixing the problem in a particular reach or location, they can lead to other management problems up or downstream Brookes, 1985). Therefore, in essence, they do not fix the problem, they just transfer it elsewhere in the catchment. For example, channelization for flood and erosion prevention, and improved drainage and navigation, can cause significant channel adjustment not just in the managed reach but also in the upstream and downstream reaches (Rinaldi et al., 2005). Channel-straightening was traditionally used for flood prevention, expansion of agricultural land and navigation. These practices shorten the channel through the removal of meander bends, increasing channel slope and mean velocity, and reducing flood levels, as friction is reduced so water moves faster downstream (Brookes, 1997). Increased channel slope also however means increased stream power, and therefore transport capacity, meaning the channel can transport more sediment than is being supplied from upstream, and this erodes the channel bed and banks in order to balance the sediment load. This leads to a destabilised reach, downstream aggradation and bank collapse (Knighton, 1998). When the Mississippi River was shortened in the 1930's and 1940's the channel gradient increased by 12%, causing huge channel instability and the formation of a wider braided channel, which required regular dredging to maintain navigation and flood protection (Winkley, 1982). In other areas flood prevention has taken place through channel-widening, to increase the volume of water the river can convey. This practice, however, decreases the stream power of the reach and therefore resulted in sedimentation within it, as it attempts to return to its original width (Brooks, 1988). As these regulated channels are ‘out of sync’ with the natural sediment regime of the river, in order for them to continue to carry out the function they were designed for, frequent maintenance is required (Thorne et al., 2010). In many cases the maintenance of these regulated channels eventually becomes uneconomical. As an increasing number of studies (Gilvear, 1999; Hooke, 2003; James, 1999; Lane et al., 1996; Raven et al., 2009; Stover and Montgomery, 2001) continue to highlight the importance of understanding bedload transfer when managing rivers, there has been a move away from these hard management practices, and a move towards soft engineering practices such as natural flood management, and river restoration, which aim to work with the natural process of the river (Sear et al., 1995).

The use of natural flood management as a way of reducing flood risk was first introduced in 2003 when the requirement for sustainable flood management was incorporated in the Water Environment and Water Services (Scotland) Act 2003 by the Scottish Government (Werritty, 2006). However, conceptual development occurred much earlier in 1990s (Sear, 1994; Sear et al., 1995). The aim of natural flood management is to provide a sustainable and cost-effective means of reducing flood risk by considering the catchment as a whole, and working with the natural processes of the river. Natural flood management works by using land management practices to address the causes of flooding, such as improved forestry practices, maintaining and restoring moorland bog, a reduction in over-grazing within the upland catchment, and the recreation of wetlands and flood-storage areas (Figure 4.1) (Howgate and Kenyon, 2008).

The aim of natural flood management, to create more resilient river channels (Werritty, 2006), is one reason why there has been an increase in the number of river restoration projects. River restoration projects aim to reverse the damage done to the river channels through straightening, dredging, embankments and damming, by recreating a naturally functioning river channel, and in doing so to restore the ecosystem services originally provided by the channel (Perfect et al., 2013). By restoring a channel, the ecological health of the river channel is improved, thereby providing services such as natural water and sediment control, carbon sequestration and reduced channel maintenance. In addition, restoration of channels can help improve the health of protected species. In many cases this involves constructing a new river channel, for example the re-meandering of a channel to slow down flood flows to the lower catchment. However, if the fundamental principles of a river catchment sediment system are not considered this can lead to instability and poor ecological integrity within the reach (Sear, 1994; 1996). Kondolf (2006) highlights this well when discussing the re-meandering of Cuneo Creek in the US, in an attempt to reduce the sedimentation within a reach which had become braided due an increased sediment supply from upstream. After a large flood the newly meandering channel was washed away and replaced with a braided channel; the developers had failed to realize that for the restored reach to be maintained, the sediment supply to it would need to match that supported by a single-thread meandering channel. However, when the River Nith in Ayrshire, Scotland was moved to allow coal mining under the natural channel, the new channel matched the width, slope and sinuosity of the former meandering channel. This has meant that instream and riparian habitats are supported by natural river processes; the upstream and downstream reaches have been unaffected and maintenance costs are minimal (Perfect, 2010; Perfect et al., 2013). These two examples highlight the importance of considering external catchment factors, and ensuring the maintenance of natural processes, when restoring and managing river channels for flood or restoration purposes, to ensure the development of a sustainable and resilient channel.

External catchment factors such as land use and land management practices, and climatic changes, also affect in-channel process such as bedload transfer, and thus channel morphology (Coulthard and Macklin, 2001; Coulthard et al., 2005; Macklin and Rumsby, 2007). Changes in these variables influence sediment transfer to the channel and the channels ability to transfer sediment, and as result can cause adjustments within channel morphology. River managers therefore require a good understanding of sediment sources within a river catchment, and transfer of sediment within a river catchment, to ensure sustainable management practices are implemented. This has become increasingly important over the last decade as current predictions suggest an increase in the magnitude and frequency of floods (Cameron, 2006; Wilby et al., 2008; Pattison and Lane, 2011; Wilby and Quinn, 2013) which in turn could potentially increase sediment delivery to river channels, and within channel sediment transfer. In addition, changing land use and land management practices affect sedimentary processes, as numerous modelling studies have demonstrated (Johnson and Whitehead, 1993; Van De Wiel et al., 2011; Zhang and Schilling, 2006), while others have suggested that these changes can make catchments more sensitive to changes in climate (Lane et al., 2007). This was later demonstrated by Macklin and Lewin in (2003) who found that river channels in the UK had become more sensitive to climatic variability post-Bronze age, when forest clearance occurred to allow for an increase in the area of agricultural land. An increase in catchment forest cover by 5.6% in the River Wharfe catchment in the Yorkshire Dales, for example, was found to reduce sediment delivery to a river channel by 80%, reducing in-channel sedimentation, leading to decreased

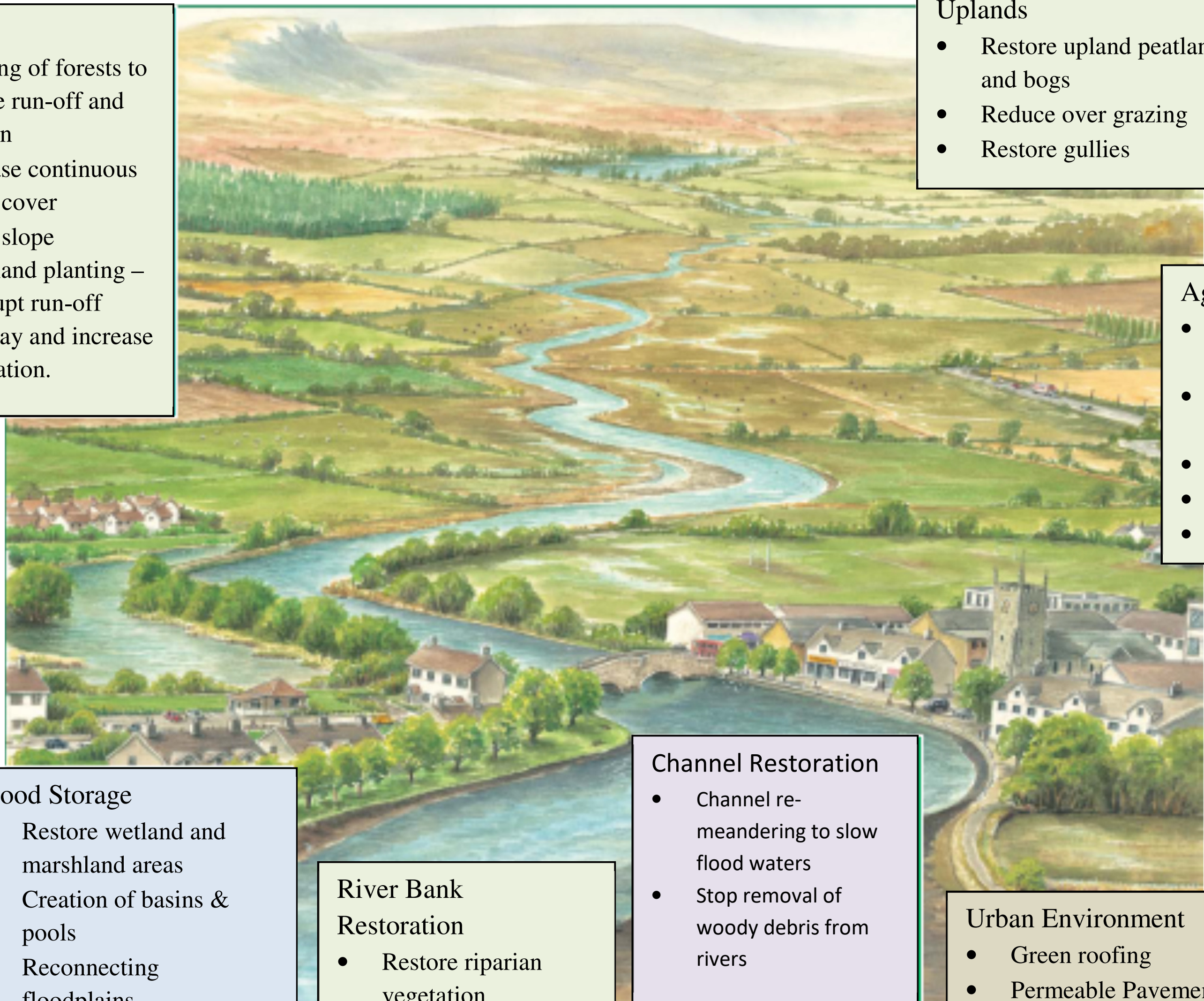


Figure 4.1: The aims of Natural Flood Management soft engineering practices is to reduce run-off and slow down flood waters by holding it in the upper catchment as long as possible. Possible ways of doing this are shown in the picture above.

Picture adapted from RSPB NFM Leaflet. https://www.rspb.org.uk/Images/naturalfloodmanagementinactionposter_tcm9-196387.pdf floodplain inundation (Lane et al., 2008). In contrast, gold mining in the Bear River in California caused episodes of high sediment delivery rates to the river channel, leading to increased channel aggradation, and thus flood risk (James, 1999). Meanwhile, urbanisation can often lead to increased channel width, or channel incision, as the river attempts to adapt to an increase in peak flows (Booth, 1990). An increase in the magnitude and frequency of floods, as is predicted with climate change, will alter the flow regime of the river, potentially giving it more power to erode and transfer sediment within the channel, and potentially increase the rate of sediment delivery to the channel. In the River Wharfe catchment in Yorkshire it has been suggested that by 2080 course sediment transfer from the surrounding catchment could increase by up to 68% compared to 1990 levels (Reid et al., 2007). However, the job of the river managers is made more difficult as channel adjustment to changes in climate can be rapid, or occur slowly over time, depending on the sensitivity of the river channel and surrounding catchment (Brunsden and Thornes, 1979; Werritty, 2002; Coulthard et al., 2005). These factors make predicting future changes in bedload transfer and morphological adjustment problematic, and this highlights the difficulty in creating a sustainable river reach within a potentially changing environment.

Currently, there are number of different methods used by geomorphologists to assess the sediment dynamics of a river, which range from field survey techniques, such as a Catchment Baseline Survey or Fluvial Audit, to simple models such as HEC-RAS, to more advanced cellular models such as CEASAR (Coulthard et al., 2000; Thorne et al., 2010). A Catchment Baseline Survey (CBS) is used to gain an understanding of the hydrology, geology, and geomorphology of an entire catchment, to allow a holistic approach to a sediment related issue within the catchment (Thorne et al., 2010). This generally involves a walk-over field survey whereby river reaches are defined, based on their process function (sediment sink, source, transfer, exchange), morphological stability (stable, widening, incising, narrowing) and conservation status (degree of natural morphology, sediment features and fluvial processes); and a desk-based study investigating current information on the river catchment under study, e.g. historical maps, surveys, and land management information. Each reach is ranked based on its 'naturalness', from 0 (heavily modified) to 10 (near-to-unaltered), and then all information on each reach is collated, and often placed within a Geographical Information System, to allow the conservation value of the whole catchment, as well as the spatial distribution of different reach types within the catchment, to be determined (Thorne et al., 2010). It can also be used to highlight key areas which could potentially undergo restoration. A Fluvial Audit (FA) aims to identify the stores, pathways and sources of sediment within a river catchment, in order to find a basis for sediment-related issues within certain reaches (bank erosion, sedimentation) within the catchment, and support the development of river restoration projects (Sear et al., 2009, 1995; Thorne, 2002). The process works on the premise that the solution to a sediment-related issues relies on finding the source of the problem, and not just treating the symptoms. Like CBS's, compiling a Fluvial Audit involves a field walk-over survey of the catchment, and a desk-based investigation looking at historic channel change and catchment factors such a rainfall, soil type and land use, which are then collated within a GIS to develop a strategy to 'fix' the sediment issue within the catchment. Studies have discussed the successful implementation of a Fluvial Audit (Eyquem, 2007; Thorne, 2002). One of the best examples of its successful implementation is in the Upper Missouri River, Montana in the US; a Fluvial Audit was carried out on this river to investigate whether the operations of the Fort Peck Dam were to blame for increased bank erosion downstream which threatened agricultural development, this was suggested by the local landowners (Darby and Thorne, 2000). However, the results of the audit showed bank erosion had decreased since the construction of the dam. Although CBS's and FA's are useful tools in providing an overview of catchment dynamics, CBS's lack a quantitative output as to the volume of sediment being stored and transported; they are both very labour intensive; and to some extent are subjective, as they rely on expert opinion. Additionally, CBS's and FA's are not predictive, and therefore river managers cannot simulate how a river system will response to different management practices (Thorne et al., 2010). As a result, many projects use one-dimensional sediment models such as HEC-RAS (Burnner, 2006; Gibson, 2006) and ISIS Sediment (ISIS, 2009) to quantitatively simulate sediment movement within rivers. These models tend to be hydraulic models with a sediment routing and bed mobility segment added. The sediment routing and bed mobility segment works based on the calculation of sediment transport rates and bed-level changes using a concept of sediment layers composed of a mix of different sediment sizes (Green, 2006). The model user can select the sediment transport equation used and the size fraction of interest. After each iteration of the model the effects of erosion and deposition are accounted for, and the channel cross-section is up-dated based on the volume of sediment entering and leaving each reach. The bed-level changes within the reach are calculated using the Exner equation, which calculates the balance of the sediment entering and leaving the reach (Green, 2006). Despite the predictive power of these one-dimensional models they still require extensive field data, such as channel roughness, closely spaced cross-sections and sediment size, and distribution data, which is often costly and time-consuming to acquire. This limits their application to reach-scale, sediment transport and channel stability issues, and the long run times of the models reduce their ability to look at reach-scale sediment dynamics over longer time scales (Thorne et al., 2010). The accuracy of these models is also dependent on the quality of the data available, and the appropriate choice of a sediment transfer equation. As a result, a very accomplished modeller is required to develop and run the models, to ensure that the correct equations are used, and the flow dynamics of the river are modelled properly.

Uncertainty arises when using physically-based models because the algorithms used to describe the different processes within sediment transport are based on numerous assumptions and processes that occur under specific physical conditions (Beven, 1989; Merritt et al., 2003). In reality many of these assumptions and physical processes are not relevant or apply when used to estimate sediment transport at the catchment scale (Merritt et al., 2003). Using psychically-based models with a large number of processes can increase model uncertainty as any inaccuracies in the input data will only amount to small inaccuracy in model output. This small error will result will accumulate with consecutive equation leading to greater model error (Merritt et al., 2003). Negating the benefit of having a more realistic representation of all the processes in sediment transport (Merritt et al., 2003). This has lead in recent years there has been an increase in the development of reduced complexity cellular models, to simulate channel change over time scales of thousands of years. This improves a river manager's ability to look at the whole river catchments, and their evolution over a variety of different temporal and spatial scales. This is challenging the process-based hydrodynamic models, which tended to only provide an insight into channel changes over short time frames, for relatively short sections of channel (Coulthard et al., 2007). Cellular models operate by dividing a catchment into a series of grid cells which water and sediment can flow between, based on the simplification of the governing rules of physics, which in turn determine landscape development. By using simplified versions of the complex flow equations used in computational fluid dynamic models, model processing time is reduced, allowing cellular models to be applied to longer reaches and larger catchments over a range of different time scales (10's to 1000's of years) (Coulthard et al., 2007). Morphological changes in the channel can also be modelled, due to the ability to simulate sediment transport processes between grid cells, giving users a valuable insight into morphological changes in the past, and potentially in the future (Coulthard et al., 2005). The capability of cellular models to do this not only increases operational speed but also addresses the scale gap issue between landscape evolution models and 1-D hydrodynamic models (Coulthard et al., 2007; Van De Wiel et al., 2011; Willgoose, 2005). Murray and Paola, (1994) were the first to use a cellular model when they simulated the morphological development of a braided river by routing its discharge over a series of grid cells which represented the channel and braid plain according to local variations in slope. A simple discharge-dependent erosion rule was applied to each cell, and the eroded material was transported to adjacent cells according to bed slope. This simple model also allowed divergent and convergent flow to be developed, and the channel width to be represented over more than one cell, which isn't possible with other Landscape Evolution Models. Despite the modelling lacking any calculations of depth or velocity, it did produce braided river patterns and reproduce downstream lateral migration bars and channels found in a braided river environment. Murray and Paola have since extensively reviewed this model (Murray and Paola, 1997), and added a vegetation growth element to look at bar stabilisation (Murray and Paola, 2003). It was this original model that created a 'paradigm shift' and inspired the development of other cellular models such as CAESAR (Coulthard et al., 2005, 2000; Coulthard and Macklin, 2001). The CAESAR model builds on the flow-routing methodology outlined by Murray and Paola (1994, 1997) by including a calculation for flow depth and multiple grains sizes for a more detailed presentation of sediment transport, and the addition of hill-slope processes such as soil-creep and land-sliding. To date CAESAR has been applied to a range of different catchments and reaches (50 to 500km^2), over a range of timescales, to investigate catchment sensitivity to environmental change (Coulthard and Macklin, 2001); and the effect of climate change, and of land use change, on catchment development (Coulthard et al., 2005). Although there are some technical issues, data collection and model validation difficulties (Nicholas, 2005), at present they provide a fairly quick method of investigating and modelling erosion, deposition and morphological change, over a range of temporal and spatial scales.

Although cellular models provide a great way of exploring morphological change, their application for looking at coarse sediment transfer and in-channel sediment issues is limited (Coulthard et al., 2007). To provide a means of looking at sediment stability problems on a catchment basis, models such as SIAM (Sediment Impact Assessment Model) and REAS (River Energy Audit Scheme) were developed (Little, 2010; Wallerstein and Soar, 2006). These models are reached-based sediment-balance models which operate at the catchment scale, meaning the risk of management practices causing channel instability can be predicted (Biedenharn et al., 2006). SIAM is a rapid assessment tool to assess the impact that different sediment management practices would have on the sediment balances of channel reaches throughout the river network. This is achieved by comparing sediment supply to sediment transport on a reach by reach basis under pre- and post-management conditions. The model is embedded within the 'Hydraulic Design' module of HEC-RAS 4.0, which allows the hydrological and hydraulic information from HEC-RAS to calculate average bedload transport rate by grain size for each user-defined reach, under a range of discharges (Thorne et al., 2010). Transport rates are then combined with flow duration data to give the average transport capacity for each reach in tonnes per year, which is compared to the average sediment supply delivered to the reach. Sediment supply is primarily from the up-stream reach, but is also from user-defined local sediment sources such as bank erosion, tributaries and sheet erosion. If the sediment supply to the reach is greater than the transport capacity of the reach, then net deposition is predicted to occur in that reach. If transport capacity of the reach is greater than the sediment supply to the reach then net erosion is predicted for that reach (Mooney, 2006). In addition, the model distinguishes between wash-load (default D_{10}, but can be user-defined), which is supply-limited, and bedload, which is transport-limited. This allows for changes in wash-load and bedload to be tracked throughout the system. The changes in the wash-load diameter downstream mean that the same particle can be wash-load in one reach and bedload in another. This means the effect of sediment sources caused by a given management practice can be more accurately predicted. A sediment source is unlikely to affect channel stability in reaches where it is part of the wash-load; however, downstream it may have a significant effect on stability, as the same particle size has transitioned into a bedload particle (Biedenharn et al., 2006). Although SIAM is an effective tool to screen out high-risk sediment management practices, it is a sediment-balance model and therefore static, meaning, unlike HEC-RAS, the channel geometry is not up-dated based on changes in erosion and deposition (Parker, 2010). This means that the output from SIAM is only suggestive of potential morphological change within a reach for a given year, or a large flood. Despite the ease of operation, rapid sediment evaluation and the ability to modify single sediment sources, SIAM's use is still often restricted because access to information on sediment sources and in-channel variables (bed material composition, sediment properties, hydrology, hydraulics) is limited, without extensive field work (Biedenharn et al., 2006).

To overcome the difficulties in data collection often imposed by SIAM, the River Energy Audit Scheme (REAS) was developed. REAS, like SIAM, is not a sediment-routing model, and instead predicts where sediment sources (scour), pathways (transfer) and sink (deposition) are located within a catchment over a period of years, based on the differences in specific stream power between consecutive reaches as the river travels downstream (Wallerstein and Soar, 2006). It uses Bagnold's (1966) concept whereby stream power gives a measure of a channel's ability to 'do work'. In doing this the model calculates the balance or imbalance in available specific stream power in each channel reach within a year, with that of next reach downstream, rather than predict sediment transport capacity or route sediment through the reach. REAS thus operates on the assumption that in a source-reach the specific stream power of the reach above is more than that required to transfer sediment, and that in a transfer-reach specific stream power is the same, and that in a sink-reach the stream power in the reach above is greater (Figure 4.2).

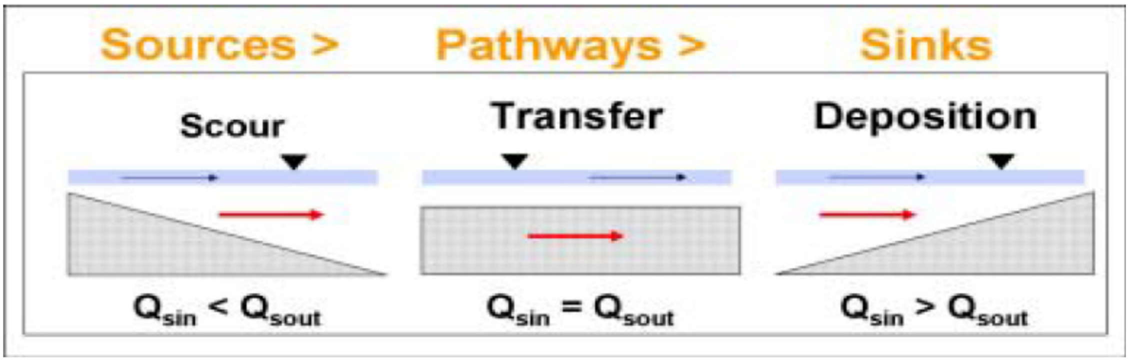


Figure 4.2: Theoretical stream power assumption behind the River Energy Audit Scheme (REAS) Model *Source: Wallerstein and Soar, 2006*

Looking at the difference in Annual Geomorphic Energy (AGE) between reaches avoids the high certainty associated with using estimates from an uncalibrated sediment transport equation (Parker, 2010). However, despite this model only requiring five input parameters (bed material particle size, flow-duration curve, channel cross-section, bed slope, and channel and floodplain roughness), in the UK there is still a lack of widely available sediment data, and full-flow duration data, to allow this data to be applied and used (Wallerstein and Soar, 2006). In addition, sediment can be supplied to a reach from outside the channel boundary, so sedimentation due to, for example, landslides will not be accounted for. It should also be noted that the relationship between stream power and sediment-transport is non-linear, meaning that REAS tends to over-estimate the impact of low flow events and under-estimate the effect of high flow events (Parker, 2010).

To address the issues with data availability outlined above, ST:REAM (Sediment Transport: Reach Equilibrium Assessment Method), a reach-based stream power balance model was developed by Parker et al. (2015), using readily available data sets. The model applies a similar philosophy to REAS, in that it is looking at changes is stream power balances between reaches in the downstream direction. However, unlike REAS, which looks at differences in available energy, ST:REAM calculates the unit bed stream power balance for each reach. Once functionally similar 50m reaches have been joined together, using Gill's (1970) global zonation algorithm, the unit-bed stream power balance is calculated by dividing the unit-bed area stream power of the median annual flood value (ω_{med}) for the one reach, by the unit-bed area stream power of the median annual flood value for the reach immediately upstream, or two reaches immediately upstream if the reach is below a confluence (Parker et al., 2015). The assumption with this method is that the ω_{med} value of a reach provides an indicator of sediment-transport capacity for that reach, and the ω_{med} of the reach up-stream gives an indicator of sediment supply. By dividing these values you get the $\omega_{balance}$ value, which if close to 1 would suggest the channel is transferring sediment; if it is significantly greater than 1 the reach is erosion-dominant; and if significantly less than 1 the reach is deposition-dominant (Parker et al., 2015). The ability of this model to use readily available data means that it provides a useful screening tool for looking for areas that could potentially lead to sedimentation or erosional hazards, and aids in flood risk management and planning. However, like REAS, sediment supply from the surrounding catchment is not included; and it assumes reach grain size is the same for the entire catchment, which in reality is extremely unlikely; which will affect model accuracy. As a result, it is recommended that the application of the model is not used in isolation, but to aid decision making when looking at sediment related catchment issues (Parker et al., 2015).

As development and availability of spatial data improves, resulting in improved calculation of stream power at the catchment scale, a number of studies and models have successfully demonstrated the ability of using stream power as a means of predicting reaches where morphological change could occur (Barker et al., 2009; Bizzi and Lerner, 2015; Parker et al., 2015; Vocal Ferencevic and Ashmore, 2012). As increases in stream flow can cause a river channel to become unstable, and thus cause them to adapt and change their morphology, it is important to understand in which reaches and at what flow a river will become unstable. In addition, if climate change brings large floods on a more frequent basis it is important to understand where, and in what part of the catchment, this is likely to occur.

This study makes use of the improvements and availability in spatial data to evaluate the using of the Scottish Environmental Protection Agency's Digital River Network (DRN) to predict areas where channel instability and fluvial hazards may occur under different flood frequencies, and in the future with climate change. In order to do this, channel depth and bedload values were estimated for each reach and added to the existing channel data already held in the DRN. Doing this allows for the ability of each 50m reach in the DRN to transport sediment to be evaluated under the predicted flood magnitudes for differing flood frequencies (1:2, 5, 10, 30, 50, 100 year), and also the same flood-frequency return intervals under a climate change scenario of medium emissions by 2080.

The ability to do this will provide river managers with a screening tool which can be used to see in which parts of the river network sediment system will become dramatically increased under current and future flood frequencies, and at what flood frequencies the river bedload within a reach will become mobile, and the reach unstable. This would allow these potential changes in sediment-transport capacity and channel-stability to be considered and studied in more detail when implementing future flood management and river restoration strategies.

4.2 METHODS

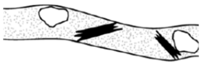
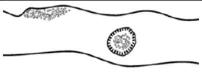
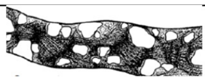
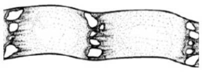
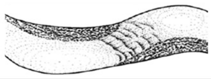
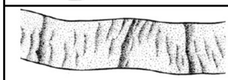
The River Dee in Aberdeenshire, Scotland was selected as a case study as it provides a good example of a Scottish upland catchment, and it also has important ecological significance, as it provides good spawning grounds for Atlantic salmon (*Salmo salar*) and is also home to the critically endangered freshwater pearl mussel (*Margaritifera margaritifera*). The River Dee is 140 km in length, and drains an area of 2100 km^2, as it flows from Wells of Dee high up in the Cairngorm Mountains through Deeside to the sea in Aberdeen. Its catchment geology consists mainly of granites and schists, with some limestone outcrops in the lower catchment (Jenkins, 1985). The river bed is predominately a mix of gravels, cobbles and boulders, with some bedrock sections. Land use is dominated by heather moorland, forestry and upland and lowland agriculture, with increasing urban development as you get closer to its mouth in Aberdeen. The annual rainfall varies from 2100mm in the Cairngorms Mountains to 841mm in Aberdeen (Cooksley, 2007).

4.2.1 SEPA's Digital River Network

SEPA's Digital River Network Model was developed using Arc Map's geospatial processing platform as part of the WFD49 typology project for SNIFFER (Greig et al., 2006c, Matheson et al., 2008). The aim of the project was to assess the ability of using geospatial data to develop a national scale database of river typology, to aid in the risk-assessment of river engineering works on the ecological status of rivers, and to guide river restoration strategies. The Digital River Network (DRN) outlines the river typology for every 50m river reach in Scotland, based on a modified version of Montgomery and Buffington's (1997) channel classification system for the Pacific North-West region of the USA (Figure 4.3).

Figure 4 3: Montgomery and Buffington 1997 Channel Classification System

(Adapted from Montgomery & Buffington, 1997; 2013, Diagram: Montgomery & Buffington, 2013)

Planform	Channel Morphology	Slope	Bedload	Reach Type	Confinement
	Colluvial	Variable	Variable	Source	Confined
	Bedrock	Variable	Rock	Transport	Confined
	Cascade	> 7.5%	Boulder	Transport	Confined
	Step-Pool	> 3-7.5%	Cobble-Boulder	Transport	Confined
	Plane-Pool	> 1-3%	Gravel-Cobble	Response	Variable
	Pool-Riffle	> 0.2 -1%	Gravel	Response	Unconfined
	Dune-Riffle	<0.2%	Sand	Response	Unconfined
	Braided	< 1%	Sand/Gravel-Cobble	Response	Unconfined

The assumption was made that different river typologies result from differing geomorphic controls (slope, geology, confinement, sinuosity) which can be identified and measured within the DRN, and used to determine river typology across Scotland (Greig et al., 2006c). The eleven river morphologies which are represented in UK rivers were allocated to one of six major river types which were labelled A to F (Figure 4.4), with each having differing levels of geomorphic resistance and resilience to change (Greig et al., 2006c). In Scotland however, Type-E, which refers to groundwater-dominated channels (chalk and limestone streams), is removed, as these channels are not found in Scotland. Extensive field studies were then carried out on the rivers Devon, Endrick and Almond, in central Scotland, to determine the typical geology, slope, confinement and sinuosity associated with different river types (Figure 4.5).

Channel Typology	Type A	Type B	Type C	Type D (D-PM)	Type F (F-PM)
Channel Morphology	Bedrock/Cascade	Step-Pool/Plane-Bed	Wandering, Braided, Plane-Riffle	Active Meandering (partially modified)	Passive Meandering (partially modified)
Slope	> 1 %	1-3 %	0.05-0.1 %	0.01-0.05 %	0.001-0.01 %
Confinement	Variable	Variable	Unconfined	Unconfined	Unconfined
Sinuosity	Low/Straight	Low/Straight	Low/Straight	Low/Sinuous	Sinuous

Figure 4.4: Channel typology developed using the Digital River Network for Scotland

This data was then used to create an automated decision-tree using the spatially collected geology, slope, sinuosity and confinement, to assign each 50m river reach a typology (Greig et al., 2006c). Validation of the DRN is two-fold, in that not only does the accuracy of the input variables need to be assessed, but also the accuracy of the resulting river typology. Field data from the River Dee (Aberdeenshire) and River Habitat Surveys (RHS) were used in order to validate the allocated river typology by the model, as well as slope and sinuosity. Greig et al., (2006c) found that river typology output matched surveyor opinion in 90 per cent, 83 per cent, 81 per cent, 50 per cent and 80 per cent of cases for bedrock, step-pool, pool-riffle, active meandering and passive meandering respectively. The lower accuracy level for active meandering reaches is because a limited number of these reaches were surveyed. From this it was concluded that the modified Montgomery and Buffington classification system, and the four predictor variables of geology, slope, sinuosity and confinement, provided a 'sound basis' for predicting natural channel morphologies in Scotland. Matheson et al., (2008) reported that when the automated decision-tree was applied to the whole of Scotland, 65% of all 50m reaches could be allocated to a 'firm-classification'. In the 35% of reaches in which channel morphology was not accurately predicted, a low confidence classification was assigned. The failure of the model to assign a firm-classification was put down to the channel being partially modified (Greig et al., 2006a), or land-use pressures leading to degradation or aggradation. Despite the results suggesting that the model performed adequately across all river typologies, data was limited, and thus further validation was carried out as data became available. However, the data from this validation process did improve search window thresholds for slope and sinuosity, and improvements to the decision-tree logic to create firm-classifications and low-confidence classifications (Matheson et al., 2008). It has also been noted that inaccuracies will occur, as variables such as vegetation, channel-width and bank material, which are also important in determining channel morphology, were not used to define it. Additionally, an earlier version of the model had 500m sampling reaches, but on review this was reduced to 50m, as 500m reaches were found to be unable to capture scale-relate changes in channel morphology and allow variability in reach typology to be measured (Matheson et al., 2008). Further 'peer-reviewing' by geomorphology experts stated that the model used a 'logical methodology' based on sound geomorphological principles, was 'fit for purpose', and made good use of available data (Greig et al., 2006a). However, all reviewers stated that the DRN could be improved over time as more data become available to improve input data, validate the model further and firm up river typology thresholds. Despite the issues with validation, it was thought that the model would provide a suitable platform for investigating catchment scale, and thus potentially national scale, changes in channel stability and sediment-transport with differing flood frequencies historically, and under climate change predictions.

The ability to do this would provide a screening tool which could highlight areas of potential change, which could then be investigated in greater detail using models such as HEC-RAS. This would mean resources could be focused on areas which are most likely to experience channel instability, which might have led to failed restoration projects and increased fluvial hazards risk. Additionally, the study would further aid in validating the DRN, and in highlighting further uses for the model.

4.2.2 Input Data-Sets and Calculation of Variables in DRN

The input data-sets used to estimate the different channel variables stored within the DRN, and any uncertainties and possible inaccuracies associated with the data, or the process of obtaining the variables, are discussed in more detail below.

4.2.2.1 River Centreline

The centreline of the river channel was derived using the waterbody Ordnance Survey Master Map polygons. This provided a very detailed skeleton of the waterways across Scotland. However, in sections where the river flows under bridges there was a gap in the digitised river network. This was corrected by combining the river polyline with the river polygons, using Master Map FME (software designed to convert, restructure and integrate OS (GB) MasterMap data and MapInfo. Inaccuracies can occur when channel avulsion occurs; meaning the digitised river channel no longer matches what is on the ground. In addition, as the digitised channel centreline is a series of straight lines it can mean that meanders appear as series of zip-zags rather than bends, meaning some points do not lie in the centre of the channel.

Figure 4.5: Prototype channel typology decision-tree developed using the Almond, Devon and Endrick rivers in central Scotland

Adapted from Greig et al., 2006c (WFD Typology Project – WFD49C)

4.2.2.2 Geology

The geology for each reach was obtained by overlaying the channel centreline with a digitised geology map from the British Geological Society. The geology of the reach was then classified into one of seven categories: bedrock, peat, drift/till (glacial sands and gravels), colluvial, alluvial, river terrace or marine. Inaccuracies in reach geology could occur due to gaps in the coverage of drift geology, or when a spur of a different geological type crosses the channel centreline, which may not by representative of what is on the ground, or picked up when creating the channel typology (Greig et al., 2006c; Matheson et al., 2008).

4.2.2.3 Slope

Channel slope represents the change in elevation from one point to another as the river flows downstream. This drop in elevation by the water causes a release of potential energy, some of which is used to mobilise sediment, and the greater the drop in elevation between two points the more energy there is available to mobilise sediment. Ensuring the slope is measured at the right resolution is therefore important, so that local variations in slope are properly represented. To ensure local variations in slope were best represented, LiDAR (Light Detection and Ranging) and NEXTMap datasets were evaluated as a means of obtaining channel slope. LiDAR is the most accurate with a vertical error of +/- 0.15m RMSE (Route Mean Squared Error), and a horizontal error of +/- 1m RMSE. The data is collected using an airborne mapping technique which uses a laser to measure the distance from the aircraft to the ground, at a spatial resolution of between 0.15m to 2m (Parker, 2010). However, the channel centreline is generated using the OS Master Map differed from the river channel on the LiDAR Digital Elevation Model, meaning that on occasion the DRN channel was flowing up the valley side, thus giving inaccurate slope values (Matheson et al., 2008). The NEXTMap DEM (digital elevation model) data is collected in the same manner as the LiDAR data, except that it uses radar signals (radio waves) rather than light to map the terrain below, at a spatial resolution of 5 meters. The accuracy of the NEXTMap DEM varies from +/-0.6m RMSE on flat terrain, to +/-2.64m RMSE on hilly terrain (Dowman et al. 2003). Despite the accuracy of the NEXTMap DEM being slightly less, and it still having the same channel overlay problems associated with the LiDAR DEM, the problem with DRN miss-match occurred less often, and the post-processing of data was easier. Additionally, as the data can be collected in poor weather, the coverage across Scotland and the UK is better. As a result, the NEXTMap data was used to measure channel slope. The distance over which slope was measured for each reach was scaled-based using the Strahler stream order value held within the channel centreline. As stream order increases the window over which slope is measured increases by 50m, so in a first order stream slope is measured over 50m, second order stream over 100m, a third order stream over 150m, and so forth. However, this distance may be shorter or longer if the reach is truncated by a loch, or is too close to the source of the river. In reaches where a negative slope occurred, the window was opened to the next downstream value which provided a non-negative slope. Negative slope values occur because in reality the earth's surface does not descend in a perfectly decreasing manner; i.e. if a cross-section of hill was taken and its profile looked at, it would be jagged, with peaks and troughs. This means that DEM have sections where the landscape is concave (troughs) and sections where it is convex (peaks). This would mean that when you measure the difference in elevation between two points on the DEM, in some cases you would be measuring the up-slope of a curve (Blaga, 2012) leading to a negative slope value. Negative slope values can also arise due to differences in scale with which data is collected and captured, and different values in which the data is stored within a geographical information system; for example, raster versus vector data (SEPA, personal communication). Slope was measured in this way because in the upper catchment, changes in slope occur over shorter distances and fairly quickly, so if the slope was taken over a 500m window then the slope value would be extremely high and thus unrepresentative of what is happening on the ground. In contrast, in the lower catchment, where changes in slope are more gradual and occur over longer distance, taking slope measurements over 50m would possibly not pick up any changes in slope, and potentially increase the chance of getting a negative slope reading.

4.2.2.4 Channel Width

Channel width was measured using the waterbody OS Master Map polygon. The perpendicular distance from the reach point to the either side of the Master Map polygon was measured, and the total distance taken as the channel width (Matheson et al., 2008). Comparison of model-generated channel width and field-measured width showed reasonable agreement, with most widths being within 5 metres of each other. When a reach point fell outside the Master Map polygon, a channel width of zero was assigned to that reach. It should also be noted that a river which appears as single line on the OS Master Map is defaulted to a channel width of one metre. In this study, channels which had a channel width of one meter were removed, as field investigation on the River Dee found that many of these channels either were not present on the ground, or were only very small ditches which would not transport bedload materials. As these one metre channels were removed in this study, the uncertainty associated with this is removed.

4.2.2.5 Confinement

Confinement provides a measure of the ratio of channel width to floodplain width. The floodplain width was calculated using SEPA's 100-year flood map as a measure of valley width. However, the map can be inaccurate in many locations, to the point at which, in some cases, the channel wasn't even within the floodplain. To solve this issue a separate code was used in reaches where mismatches occurred, which assigned an average width using values from the next reach upstream or downstream (Matheson et al., 2008). This parameter required the most 'human intervention' due to the lack of availability of good quality data sets, and being unable to automatically generate 'sensible' floodplain values in sinuous reaches. The values generated for each reach were used to classify each reach into one of three groups: confined (1 and < 2), semi-confined (2 and < 4) and unconfined (>4). When modelled confinement categories were compared to field observations, 75% of the reaches surveyed matched the confinement categories assigned by the model (Greig et al., 2006b).

4.2.2.6 Sinuosity

Sinuosity was calculated as the ratio between channel length and valley length. The valley length was the straight-line distance from the start to the end of a reach, and stream length was the length of the stream within the same reach. The length of the window used to measure sinuosity was based on the Strahler stream order. Each increase in stream order increased the sinuosity window length by 1000m, therefore 1st order streams had a window of 1000m, 2nd order streams had a window of 2000m and 3rd order streams had a window of 3000m, and so forth. Channels which had ratios of less than 1.05 were considered straight, a ratio between 1.05 and less than 1.5 was considered low sinuosity, and a value greater than 1.5 was considered meandering (Greig et al., 2006b, c). When the sinuosity values generated by the DRN were compared to channel patterns on a 1:50,000 OS Map, it was found that in 'most' cases the sinuosity values were similar to those observed. The DRN was found to underestimate sinuosity when the channel had been simplified, particular in smaller channels (<5 metres wide) because meandering had been omitted when the DRN was created from 1: 50,000 scale maps. Overestimation only occurred when the valley tended to curve, so the start and end points used to measure valley length were underestimated (Greig et al., 2006c).

4.2.2.7 Channel Depth

Channel Depth was not calculated in the original DRN. However, it has been estimated and added to the DRN as part of this study, so that rate of bedload transport can be evaluated. Channel depth was estimated within ArcMap using the model builder (Figure 4.6). This process involved extracting the depth values across the whole width of the channel at each 50m point on the channel centre line, using the NEXTMap DEM. The average value from all the depth values taken was then used as the channel depth. The average value was taken to allow for the changes in depth which can occur as you walk from one side of the channel to the other. As with estimating channel width, measurement errors occurred when the DEM did not match properly with the water body polygon, meaning that in some cases all the depth values were in the channel and did not take into the account the drop from the banks on either side. Also, as the NEXTMap DEM only has a 5m resolution, this means that channels which have a width of less than 5m will possibly be allocated a river depth of close to zero, as all the depth values will potentially come from the same 5m grid cell. This might lead to an overestimation of bedload transport rate in affected reaches. However, this issue should be limited to the source areas of upland tributaries where channels tend to be narrower, rather than the main stem of the river and the lower section of tributaries, where channels are characteristically wider. When compared to field data along the River Dee from the Linn of Dee to Clunie Water tributary near Braemar, it was found that on average the model under-predicts the channel by 52cm. In transfer, depositional, erosional and channel-shifting sections of the river it was found that the model under-predicted channel depth by approximately 40cm, 54cm, 41cm and 27cm respectively.

The pattern of changing depth, however, was found to be similar between the field measurements and the NEXTMap DEM (Figure 4.7), meaning that the change in the channels ability to transfer material will be fairly consistent. Although these discrepancies would lead to inaccuracies in model prediction, this was the best method available to provide an estimate of river depth. Through time, better spatial data may become available to improve the model output.

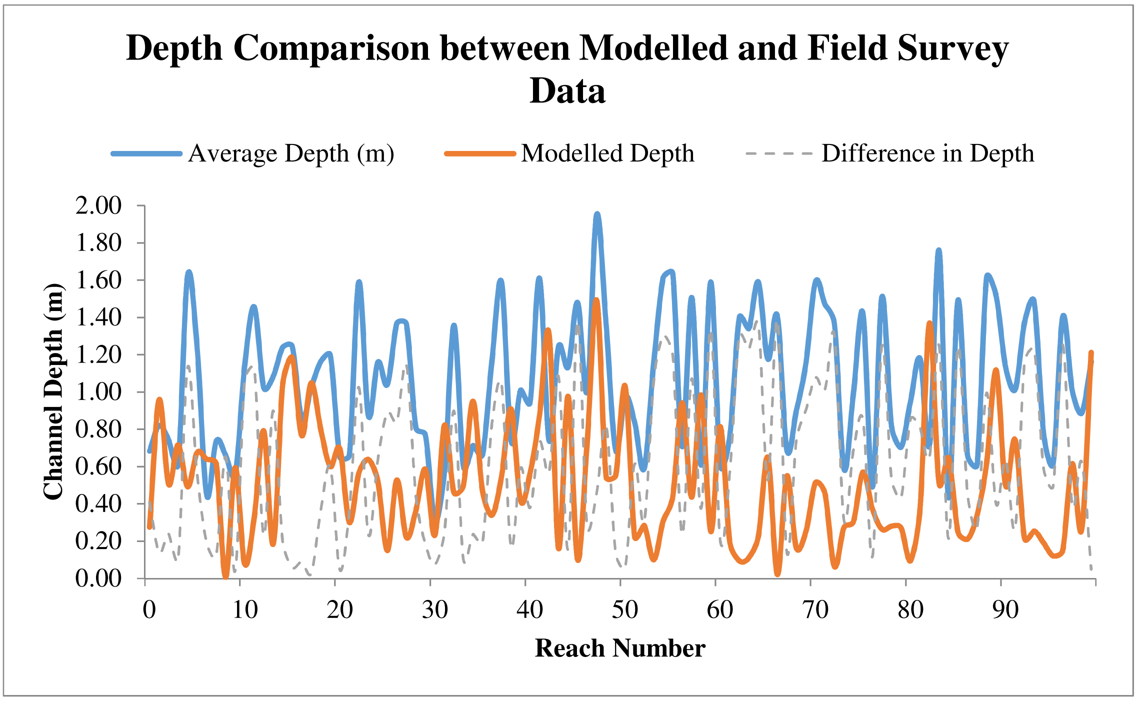


Figure 4.7: Comparison between modelled and field survey depth measurements.

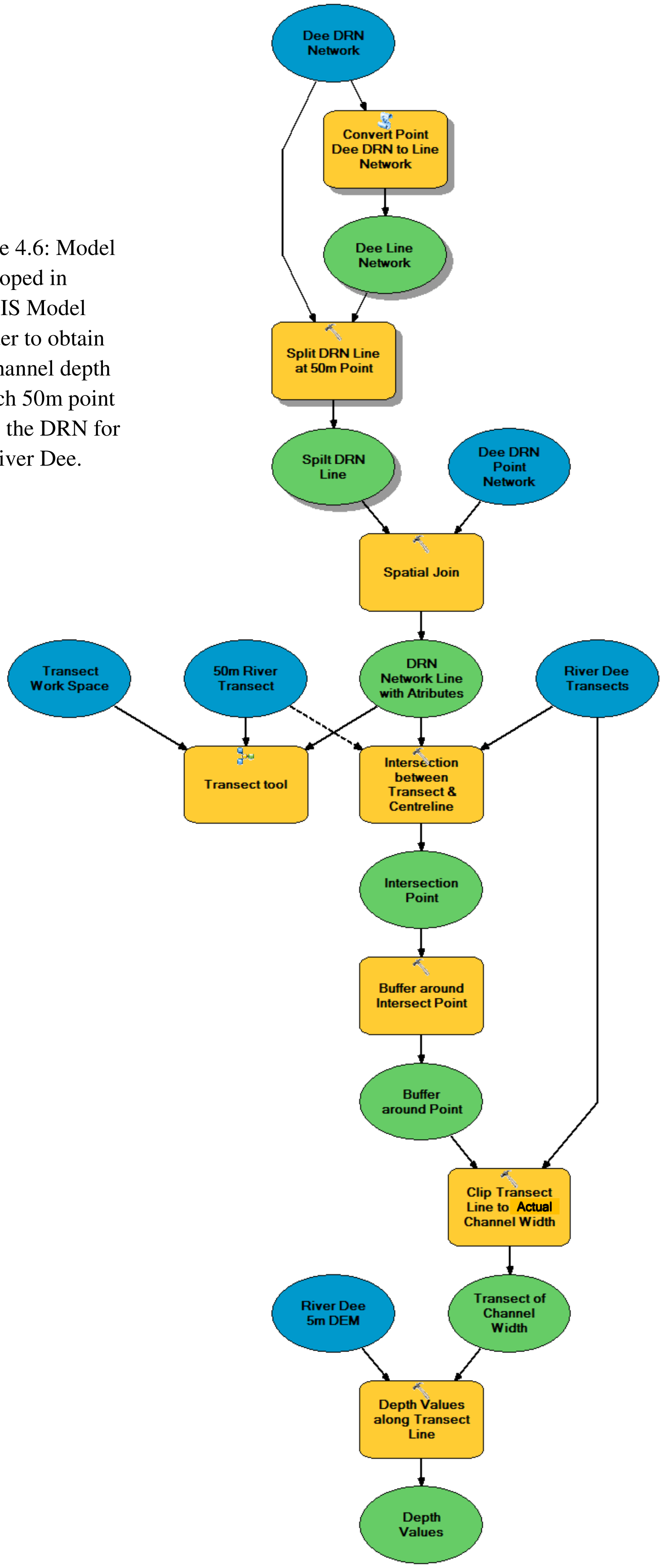


Figure 4.6: Model developed in ArcGIS Model Builder to obtain the channel depth of each 50m point along the DRN for the River Dee.

4.2.2.8 Channel Bedload

Each river typology outlined in the DRN was assigned a grainsize value thought to be representative of the D_{84} of that typology type. These are outlined in Table 4.1. The D_{84} was selected because several studies have shown that when the D_{84} grain size becomes mobile within a reach it will start to become unstable, and potentially start to adjust its morphology (Booth, 1990; Carling, 1988; Olsen et al., 1997; Pickup and Warner, 1976). The grainsize value assigned to each river type was based on field data, literature reviews (Greig et al., 2006c; Thompson and Croke, 2008, Lenzi et al., 2004), and expert opinion. . When the selected values were compared to the field data collected on the River Dee, there was good agreement. In addition, the trend and pattern of change of bedload size between the different river typologies was consistent, in that Type B reaches tended to have a higher D_{84} than Type C reaches, and Type C reaches to have a higher D_{84} than Type D reaches, and so forth. This means, in terms of modelling, that even if the bedload value is not exactly right, the relationship between the reaches in terms of bedload size will still be representative. Grain size data for each SEPA channel type (Type A to F) was collected during the field survey of the River Dee. Wolmon pebble counts were carried out every 100 metres along the 5km survey reach or when a change in channel type occurred. The D_{84} was calculated for each reach and used guide the choice of grain size for each channel type in the model.

Table 4.1: Digitial River Network Channel Typologies

River Typology	Channel Morphologies	Representative Grain Size	D84 Value from Field Data
Type A	Bedlock/Cascade	500 mm	> 256 mm
Type B	Step-pool/Plane-bed	210 mm	190-256 mm
Type C	Wandering, Braided, Plane-riffle	120 mm	90-130 mm
Type D	Low Gradient Active Meandering	90 mm	70-100 mm
Type E	Groundwater Dominated	N/A	N/A
Type F	Low Gradient Passive Meandering	45 mm	40-50 mm

4.2.3 Calculating Specific Stream Power

4.2.3.1 Calculating Specific Stream Power

Bagnold, (1980, 1977) proposed a method of predicting the bedload transport rate by predicting the mean value of stream power per unit area of the river bed, now termed specific or unit stream power. This is defined as:

$$\omega = \frac{\rho g Q S}{w}$$

where Q is the discharge (m s^{-1}), w is the width of the water surface in meters, S is the longitudinal slope in m m^{-1}, ρ is the specific weight of water and g is the acceleration due to gravity in m s^{-2}. However, it should be noted that Bagnold omitted g in his equations. The specific stream power of a reach provides an indication of the rate of potential energy that is supplied to a unit area of the river bed, and therefore the power the river reach has to perform geomorphic work (Ferguson, 2005; Knighton, 1999). The specific stream power values for each river reach were calculated using the data from Digital River Network, namely slope, discharge and channel width.

4.2.3.2 Calculating Critical Specific Stream Power

Sediment transfer within the river system is assumed to occur at a very slow rate until a critical level of discharge or stream power is achieved. Once this critical value is achieved sediment transfer will occur at a 'faster-than-linear' rate (Ferguson, 2005). Bagnold, (1980) proposed that the critical stream power required to increase bedload transport non-linearly could be calculated by:

$$\omega_c = c_1 D^{1.5} \log(\frac{c_2 d}{D})$$

where c_1 and c_2 are numerical constants, d is the depth of the channel in metres, *D* is the diameter of the particle sized moved in metres, and the logarithm is to the base 10. The constants given by Bagnold (1980) are c_1 – 290 and c^2 = 12, although where these values come from is not explained. Although this equation has been widely used in the literature there have been some criticism made about it (Ferguson, 2005; Petit et al., 2005). Firstly, the two D values in the equation refer to two different things: the size of particle entrained by the flow, and the particle size that represents flow resistance; however, both are given the same value. In reality, the coarser particles on the bed dominate flow resistance, whereas the finer grains on the bed are usually the ones transferred, so ideally the same value should not be used for both (Ferguson, 2005). Secondly, the critical stream power equation requires a depth value for each flow under which bedload transport is being investigated (Ferguson, 2005). This removes the original advantage of using stream power over shear stress. Finally, the Bagnold equation for critical stream power does not take into account grain-hiding, which means it can take more energy to move smaller particles because they are sheltered by larger grains, whereas larger grains protrude making them easier to move. As a result, Ferguson's (2005) equation for critical stream power, which addresses these issues, was used to calculate critical stream power in this study. Ferguson's critical stream power equation is:

$$\omega_{ci} = 0.113 D_b^{1.5} \log\left[\frac{0.73}{S}\left(\frac{D_i}{d_b}\right)^{0.4}\right]\left(\frac{D_i}{d_b}\right)^{0.6}$$

where D_b is the median grain size for the whole bed in metres, Di is the grain size entrained by the flow in metres, S is channel slope in m m^{-1}, and the logarithm is to the base 10. 0.4 and 0.6 are constants, which represent the hiding function, 0.73 is a measure of the sediment density and submerged specific gravity, and 0.113 is a measure of gravity, roughness, sediment density, the specific weight of water and shear stress.

4.2.3.3 Calculating Bedload Transport Rate

Bedload transport formulae in rivers is based on one of four principles. Gomez and Church (1989) outlines these principles as: stream power (Bagnold, 1980), bed shear stress (du Boys, 1879), stream discharge (Schoklitsch, 1934) and stochastic functions of sediment movement (Einstein, 1950). Using bed shear stress, stream discharge and stochastic functions of sediment movement principles to estimate sediment transport require detailed hydraulic information such as shear velocity (Poorhosein et al., 2014). These formulas are therefore best placed to estimate bedload transport in situations where knowledge of sediment transport is required to deal with localised issues, such as scour near infrastructure or high levels deposition, which is increasing flood risk (Gomez and Church, 1989). A stream power equation however, can be used in situations where it is difficult to gain detailed hydraulic information as it still provides a straightforward scale correlation between the power of the channel and resisting forces of the bed (Gomez and Church, 1989). As in this study the rate of bedload transport is to be measured across an entire catchment, it was not possible within the time available to gain detailed hydraulic information for the whole catchment. For this reason, estimates of the rate of bedload transport across the River Dee catchment where calculated using a stream power bedload transport equation. The bedload transport rate for each reach was calculated using Bagnold's (1980) formula for bedload transport. The equation, like many other sediment transport equations, relies on the relationship between stream power and critical stream power. It expresses the rate at which bedload of a set particle size can move through each reach for a given flow. The formula is expressed below:

$$i_b = (\omega - \omega_{ci})^{3/2} \, Y^{-2/3} \, D^{-1/2}$$

Where ω is specific stream power in kg m s^{-1}, ω_{ci} is critical stream power in kg m/s^{-1}, Y is mean channel depth in meters, and D is the grain size to be entrained in meters. It should also be noted that this equation assumes a rectangular channel, which of course in natural channels is unlikely to be the case. In natural channels, the depth of the channel will vary and stream powers will vary across a cross section. In a rectangular channel, the flow depth and stream power will be consistent across the reach meaning this equation will most likely over predict the rate of bedload transport.

4.2.3 Analysis of the Model Output

The bedload transport rate for each reach across the catchment was calculated for historic flood magnitudes, for flood frequencies of 1: 2, 5, 10, 30, 50 and 100 years. This was then repeated for the same flood frequency intervals but with the increase in magnitude expected with the predicted changes in climate associated with medium emissions by 2080. There was an 18% increase for all flood magnitudes, except for a 1:10 flood magnitude which increased by 20%. The discharge values for the climate change flood frequencies were calculated using the same method referred to in Chapter 3. If the rate of bedload transport for a D_{84} particle within a reach was greater than 94 t m s^{-1} then that reach was considered to have a high sediment transport capacity, and decreased levels of channel stability. These river reaches were labelled as 'highly unstable'. If the rate of bedload transport for a D_{84} particle was less than 28 t m s^{-1} then the reach was considered to have a low sediment transport capacity, and increased levels of channel stability. These reaches were labelled as 'minor instability'. If the rate of bedload transport for a D_{84} particle within a reach was between 28 t m s^{-1} and 94 t m s^{-1} then the reach was considered to have moderate sediment transport capacity and moderate levels of channel stability.

These reaches were labelled as 'unstable' reaches. The thresholds for each reach are summarised in Table 4.2.

Table 4.2 Reach Classification

Minor Instability	< 28 t m s^{-1}
Unstable	> 28 and < 94 m s^{-1}
Highly Unstable	> 94 t m s^{-1}

These thresholds were developed using field data from the River Dee. A 5km section of the River Dee from the Linn of Dee, to Braemar was walked, and each reach labelled as being: 'stable' or showing limited evidence of channel change, 'unstable' when there was evidence of lesser amounts of bank erosion and channel adjustment, or 'highly unstable' when there was evidence of channel shifting, serve bank erosion or channel avulsion. This section of the River Dee included a range of different channel types common with the River Dee catchment. These were bedrock, plane-bed, active meandering, wandering, plane-riffle and passive meandering. Thus at least one channel of the channel morphologies within SEPA's Type A to F classification was surveyed. The modelled rate of bedload transport for each of the 100 reaches surveyed was then recorded. A box plot was then drawn to identify any clear thresholds between the channel instability categories (Figure 4.8). The quartile figures for each channel stability category are shown in Table 4.3.

Table 4.3 Interquartile Ranges for Channel Stability Categories (t m s^{-1})

	Quartile 1	Median	Quartile 3
Minor Instability	1.46	17.89	32.61
Unstable	28.71	39.64	52.34
Highly Unstable	94.02	112.91	198.14

An upper threshold of 28 t m^{2} s^{-1} was selected to represent channels with minor instability. 28 t m^{2} s^{-1} is the quartile 1 value for unstable reaches. This value was selected as there was an overlap between the quartile 3 value of the ‘minor instability’ reaches and quartile 1 value of ‘unstable’ reaches. The assumption being that if the quartile 3 value for minor instability reaches was used as the upper threshold for classifying reaches with ‘minor instability’ there would have been an increased probability of ‘unstable’ reaches being identified as being stable (minor instability). As a result, a worst-case scenario approach was taken. By selecting the quartile 1 value of unstable reaches as the threshold between ‘minor instability’ and ‘unstable’ reaches, as the probability of a channel reach below this threshold undergoing only minor adjustments in channel morphology is high. Channels with a rate of bedload transport over 94 t m^{2} s^{-1} were classified as being ‘highly unstable’. This is the quartile 1 value for field channels categorised has being ‘highly unstable’, meaning that probability of a channel reach above this threshold undergoing significant channel adjustment at the specified flood magnitude is high. Kruskal-Wallis testing confirmed that there was statistically significant difference between the different channel stability categories (H=90.81, 2 d.f., **P**=<0.0001).

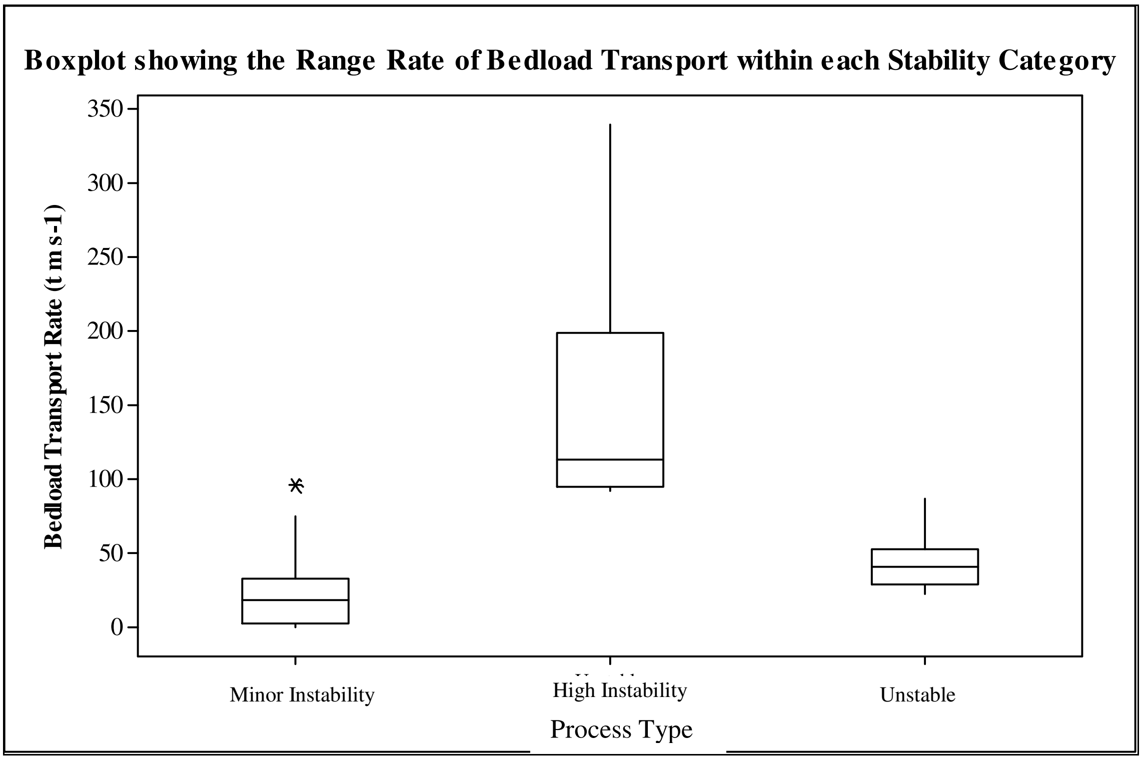


Figure 4.8 Boxplot showing range of bedload transport rates associated with each channel process type

However, it is important to note that the end-user of the model can also modify these groupings to best fit the river under investigation, or the project being managed. The differences in the number of reaches labelled 'minor instability', 'unstable' and 'highly unstable' for each flood frequency were then compared, and the locations where instability primarily occurred reviewed and summarised.

4.3 RESULTS

4.3.1 Channel Stability

The results (Table 4.4, Table 4.5, Figure 4.9 and Figure 4.10) show that as the flood-frequency return interval increases from a 1:2 year flood flow to a 1:100 year flood flow, so does the number of unstable reaches within the catchment. This would be expected, as the higher discharges associated with the larger return intervals would provide the channels with more power to erode and transport sediment. Using the thresholds devised in this study (Table 4.2), to distinguish between reaches of minor and high-channel instability, it is suggested that the River Dee is fairly resilient to high magnitude flood events. Even under a climate change enhanced 1:100 year flood flow, less than 10% of river reaches are classed as 'highly unstable' and 11% are classed as 'unstable'. Thus 79% of all river reaches across the River Dee catchment are predicted to have only minor changes in channel stability under a climate enhanced 1:100 year flood.

Under a climate change scenario, it was observed that a flood flow with a return interval of 2 years will increase the number of 'highly unstable' reaches in the River Dee to historic 1:5 year flood conditions (i.e akin to a more than doubling of channel instability). A similar result was found between a 1:30 year flood under climate change and a historic 1:50 year flood, thus in the future the channel instability normally experienced every 50 years will now probably be experienced every 30 years. Finally, under a 1:50 year flood, under a climate change scenario the River Dee will experience the channel instability levels associated with a historic 1:100 year flood flow. This means the time between historic high magnitude flow events will decrease, reducing the time available for channels to recover and return to their previous channel geometry. As a result, it would be expected that some reaches will adapt their morphology to accommodate the increased volume of water and sediment, and reduced recovery times between large flood events.

Table 4.4 Number of Reaches within each Stability Category with Changing Flood Frequency						
Return Interval	**1:2**	**1:5**	**1:10**	**1:30**	**1:50**	**1:100**
Minor Instability	11916	11643	11366	10849	10562	10152
Unstable	285	379	498	774	912	1057
Highly Unstable	78	257	415	656	805	1070
Return Interval	**1:2CC**	**1:5CC**	**1:10CC**	**1:30CC**	**1:50CC**	**1:100CC**
Minor Instability	11750	11363	10976	10384	10079	9689
Unstable	160	506	719	973	1064	1135
Highly Unstable	285	410	584	922	1136	1455
Key: CC: Climate Change						

When the percentage increase in the number of 'highly unstable' reaches under historic flood-magnitude return intervals was compared to those under a climate change scenario, it was found that there was between a 0.5% to 2.5% increase in the number of 'highly unstable' reaches. The greatest increase in the number in 'highly unstable' reaches under a climate change scenario occurred for a 1:30 year flood and 1:10 year flood at 2.58% and 2.48% respectively (Table 4.6).

When the change in the number of 'unstable' reaches was examined it was found that under a climate change scenario 1:5, 1:30 and 1:50 year floods would be the equivalent of an historic 1:10, 1:50, 1:100 year flood respectively. Under a climate change scenario, the number of 'unstable' reaches increased by between 0% and 3.24% (Table 4.6) compared to historic levels. The number of 'unstable' reaches was found to increase as the flood-frequency return interval increased (Table 4.6).

Table 4.5 Percentage Number of Reaches within each Stability Category with Changing Flood Frequency						
Return Interval	**1:2**	**1:5**	**1:10**	**1:30**	**1:50**	**1:100**
Minor Instability	97.04%	94.82%	92.56%	88.35%	86.02%	82.68%
Unstable	2.32%	3.09%	4.06%	6.30%	7.43%	8.61%
Highly Unstable	0.64%	2.09%	3.38%	5.34%	6.56%	8.71%
Return Interval	**1:2CC**	**1:5CC**	**1:10CC**	**1:30CC**	**1:50CC**	**1:100CC**
Minor Instability	95.69%	92.54%	89.39%	84.57%	82.08%	78.91%
Unstable	2.32%	3.34%	4.76%	7.51%	9.25%	11.85%
Highly Unstable	1.30%	4.12%	5.86%	7.92%	8.67%	9.24%
Key: CC: Climate Change						

The modelling suggests that the main channel of the River Dee is more stable, in terms of bedload dynamics, than its upland tributaries. Under historic flood frequency magnitudes, a 1:100 year flood flow is required before over 5% of all main channel reaches become ‘unstable’ (Table 4.7), but only a 1:30 year flood is required for over 5% of all tributary reaches to become ‘unstable’ (Table 4.8).

Table 4.6: Percentage Change in each Stability Category with Climate Change for each Flood Frequency

Return Interval	1:2	1:5	1:10	1:30	1:50	1:100
Minor Instability	-1.35%	-2.28%	-3.18%	-3.79%	-3.93%	-3.77%
Unstable	0.00%	0.25%	0.70%	1.21%	1.82%	3.24%
Highly Unstable	0.67%	2.03%	2.48%	2.58%	2.11%	0.53%

a)

b)

c)

d)

e)

f)

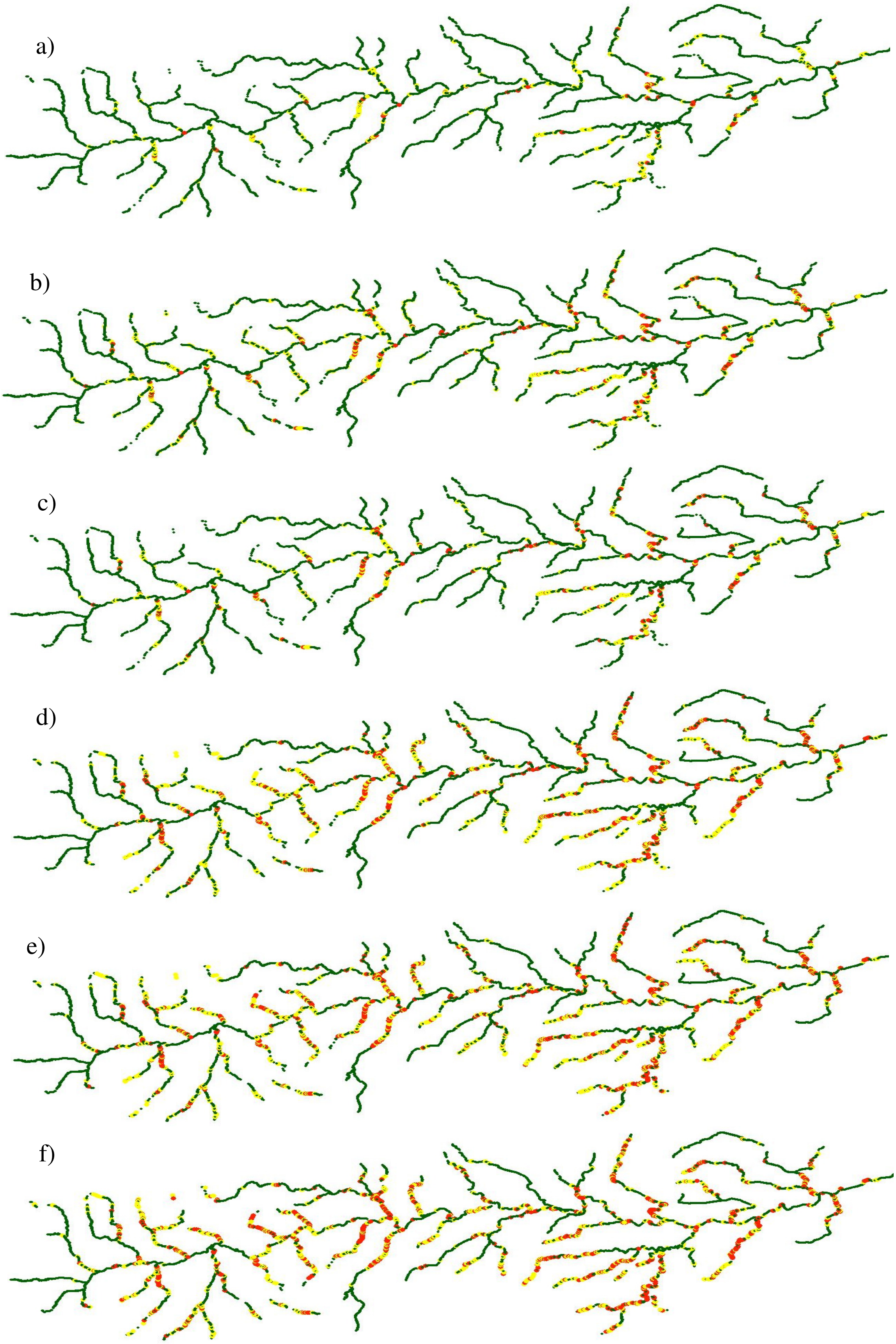


Figure 4.9: Composite of stream power maps created in ArcMap showing minor instability (green), unstable (yellow) and high instability (red) for the six different flood return intervals: (a) 1:2 year, (b) 1:5 year (c) 1:10 year (d) 1:30 year, (e) 1:50 year and (f) 1:100 year.

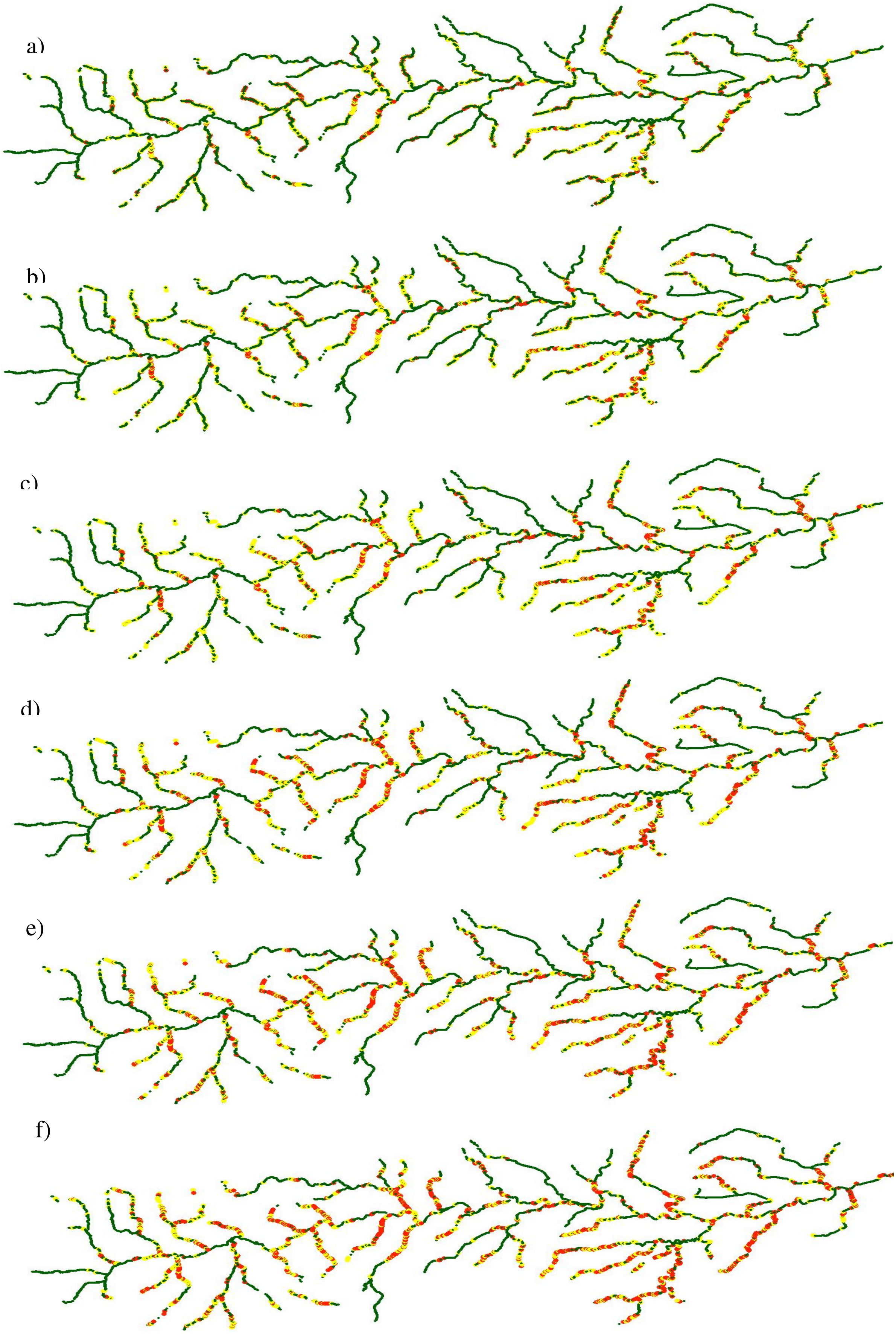


Figure 4.10: Composite of stream power maps created in ArcMap showing minor instability (green), unstable (yellow) and high instability (red) for the six different flood return intervals under a climate change scenario (medium emissions by 2080): (a) 1:2 year, (b) 1:5 year (c) 1:10 year (d) 1:30 year, (e) 1:50 year and (f) 1:100 year.

Table 4.8 Number of Stable, Unstable and Threshold Reaches with Changing Flood Frequency - Tributaries						
	1:2	1:5	1:10	1:30	1:50	1:100
Minor Instability	96.73%	94.28%	91.69%	87.04%	84.58%	81.09%
Unstable	2.56%	3.37%	4.54%	7.01%	8.12%	9.13%
Highly Unstable	0.71%	2.35%	3.78%	5.96%	7.30%	9.79%
	1:2 CC	1:5 CC	1:10 CC	1:30 CC	1:50 CC	1:100 CC
Minor Instability	95.27%	91.66%	88.20%	83.05%	80.48%	77.15%
Unstable	3.29%	4.62%	6.54%	8.55%	9.13%	9.66%
Highly Unstable	1.44%	3.72%	5.26%	8.41%	10.40%	13.19%

When the difference between 'highly unstable' reaches was compared between the main channel and the upland tributaries, it was established that, even at 1:100 flood flows, less than 5% of reaches become 'highly unstable' in the main channel, whereas in the tributaries over 5% of reaches become 'highly unstable' at 1:30 year flood flow. One possible reason for this difference between main channel reaches and tributary reaches is

due to the steeper slopes and narrower channel widths in the tributaries, providing the channels with greater power to erode and transport bedload material; an observation which was made when reviewing the DRN data in ArcMap. Along the main channel, instability tended to occur close to tributary junctions, or in sections of the channel which showed signs of avulsion or mid-channel bar development. In the tributaries, channel instability again tended to occur close to the tributary junctions, and in areas with steeper slopes. Channel instability ('unstable' and 'highly unstable' reaches) was also investigated around key Deeside towns, to highlight towns with higher flood hazard risks. Channel instability issues were primarily identified along the Clunie Water as it flows through Braemar to join the River Dee, upstream of Ballater town, particularly along the A93 close to Abergeldie Castle and downstream of Aboyne; at historic 1:10 year flood flows. The greatest amount of channel instability was seen close to the town of Peterculter, in which channel instability occurred at historic 1:2 year flood flows.

Table 4.7 Number of Stable, Unstable and Threshold Reaches with Changing Flood Frequency - Main Channel						
	1:2	1:5	1:10	1:30	1:50	1:100
Minor Instability	98.31%	96.99%	96.13%	93.70%	91.85%	89.13%
Unstable	1.36%	1.93%	2.10%	3.46%	4.61%	6.50%
Highly Unstable	0.33%	1.07%	1.77%	2.84%	3.54%	4.36%
	1:2 CC	1:5 CC	1:10 CC	1:30 CC	1:50 CC	1:100 CC
Minor Instability	97.41%	96.09%	94.20%	90.74%	88.60%	86.04%
Unstable	1.85%	2.10%	3.09%	5.39%	6.79%	7.53%
Highly Unstable	0.74%	1.81%	2.72%	3.87%	4.61%	6.42%

A climate change scenario was also found to increase the number of unstable ('unstable' and 'highly unstable') reaches, more in the tributaries compared to the main channel. The same pattern was found for the increase in 'highly unstable' reaches between the main channel tributaries (Table 4.9, Table, 4.10 and Figure 4.9). When the increase in 'unstable' reaches was investigated it was found that at 1:30, 1:50 and 1:100 year floods the increase in 'unstable' reaches was greater in the main channel rather than the tributaries. For a 1:50 and 1:100 year flood, the increase in 'unstable' reaches in the main channel with a climate change scenario is almost more than double the increase in the tributaries (Table 4.7 and Table 4.8). The greatest increase in channel instability with a climate change scenario in both the main channel and the tributaries was at 1:50 year flood. This could possibly mean that an historic 1:50 year flood, and a climate change enhanced 1:30 year flood, represent a key threshold for channel changes for many reaches across the River Dee catchment. To verify this, however, further work needs doing, with detailed modelling, or using old maps and photos before and after a flood event of a known magnitude.

Table 4.9: Percentage Change in each Stability Category with Climate Change for each Flood Frequency - Main Channel

Return Interval	1:2	1:5	1:10	1:30	1:50	1:100
Minor Instability	-0.91%	-0.91%	-1.93%	-2.96%	-3.25%	-3.09%
Unstable	0.49%	0.16%	0.99%	1.93%	2.18%	1.03%
Highly Unstable	0.41%	0.74%	0.95%	1.03%	1.07%	2.06%

4.3.2 Bedload Transport

As with the number of unstable channel reaches, the average, median and maximum rate of bedload transport across the whole catchment increased, as flood frequency magnitude increased (Table 4.11), as would be expected. The average rate of bedload transport increased from 2.47 t m s^{-1} under a 1:2 year flood, to 35.62 t m s^{-1} under a 1:100 year flood (Table 4.11). The median rate of bedload transport increased from 0.4 t m s^{-1} under a 1:2 year flood flow, to 0.74 t m s^{-1} under a 1:100 year flood (Table 4.10). With climate change the average and median rate of bedload transport across the whole catchment increased to 4.05 t m s^{-1} and 0.07 t m s^{-1} for a 1:2 year flood respectively, and 58.54 t m s^{-1} and 1.21 t m s^{-1} for a 1:100 year flood respectively. Climate change was found to increase the average and median rate of bedload transport by around 64% for all flood frequency return intervals.

Table 4.10: Percentage Change in each Stability Category with Climate Change for each Flood Frequency - Tributaries

Return Interval	1:2	1:5	1:10	1:30	1:50	1:100
Minor Instability	-1.46%	-2.62%	-3.48%	-3.99%	-4.10%	-3.94%
Unstable	0.73%	1.25%	2.00%	1.54%	1.01%	0.54%
Highly Unstable	0.73%	1.37%	1.48%	2.45%	3.10%	3.40%

The one exception was for a 1:10 year flood, where climate change increased the average and median rate of bedload transport by around 73%. As with the number of unstable reaches under climate change, the rate of bedload transport during a historic 1:10 year flood flow will now potentially occur every 1:5 years. This same phenomenon is observed between a historic 1:50 year flood flow and a 1:30 year flood flow under climate change, and a historic 1:100 year flood flow and a 1:50 year flood flow under climate change. The very high maximum values (greater than 600 t m s^{-1}) were often found in channel reaches where waterfalls were present, such as the Falls of Feugh on the Water of Feugh tributary which joins the River Dee at Banchory, or in sections of channel with very high slope values (> 5%), and narrow sections of channel (< 3 meters).

Table 4.11 Average, Median and Maximum Rates of Bedload Transport for Whole Catchment (t m s^{-1})

	1:2	1:5	1:10	1:30	1:50	1:100
Average RoBT	2.47	5.36	8.57	17.08	23.28	35.62
Median RoBT	0.04	0.10	0.17	0.36	0.49	0.74
Maximum RoBT	5685	11649	17858	35579	48040	73521
	1:2 CC	1:5 CC	1:10 CC	1:30 CC	1:50 CC	1:100 CC
Average RoBT	4.05	8.82	14.81	28.06	38.25	58.54
Median RoBT	0.07	0.17	0.30	0.59	0.80	1.21
Maximum RoBT	9343	19144	30860	58461	78935	120802
Increase with Climate Change						
Average RoBT	64.03%	64.34%	72.83%	64.33%	64.32%	64.32%
Median RoBT	65.10%	64.56%	73.45%	64.82%	64.62%	64.52%
Maximum RoBT	64.35%	64.34%	72.81%	64.31%	64.31%	64.31%

Key: CC - Climate Change

As with the number of unstable reaches, average, median and maximum rates of bedload transport were higher in the tributaries than in the main channel (Table 4.12 and Table 4.13). This is probably because of the steeper slopes and narrower channel widths within the tributaries, which provide the channel with more power to erode and transport bedload. On average, the rate of bedload transport in the tributaries was 36% higher than in the main channel. The only exception to this was during a 1:2 year flood flow where rate of bedload transport was 60% higher in the tributaries than in the main channel. Across the whole of the catchment, climate change increases the average, median and maximum rate of bedload transport by around 64% in both the main channel and the tributaries. The exception to this is a 1:10 year flood flow, where the percentage increase in the average, median and maximum rate of bedload transport is around 73%.

Table 4.12 Average, Median and Maximum Rates of Bedload Transport for Main Channel (t m s^{-1})

	1:2	1:5	1:10	1:30	1:50	1:100
Average RoBT	2.47	5.36	8.57	17.08	23.28	35.62
Median RoBT	0.03	0.07	0.11	0.21	0.28	0.43
Maximum RoBT	952	2091	3409	6843	9328	14343
	1:2 CC	1:5 CC	1:10 CC	1:30 CC	1:50 CC	1:100 CC
Average RoBT	4.05	8.82	14.81	28.06	38.25	58.54
Median RoBT	0.05	0.11	0.18	0.34	0.46	0.70
Maximum RoBT	1564	3436	5891	11243	15327	23567
Increase with Climate Change						
Average RoBT	64.35%	64.34%	72.83%	64.33%	64.32%	64.32%
Median RoBT	64.42%	64.37%	72.87%	64.34%	64.43%	64.34%
Maximum RoBT	64.31%	64.31%	72.81%	64.31%	64.31%	64.31%

Key: CC - Climate Change

Table 4.14 Average and Median Rate of Bedload Transport for Type A, B and C River Typologies for Historic Flood Frequency Magnitudes and with Climate Change Flood Frequency Magnitudes

	Flood Return Interval	Average (Historic) t m s^{-1}	Median (Historic) t m s^{-1}	Average (Climate Change) t m s^{-1}	Median (Climate change) t m s-[1]	Percentage Increase with Climate Change Average	Percentage Increase with Climate Change Median
Type A	2	7.42	0.41	11.64	0.67	56.87%	63.41%
	5	15.81	0.96	25.98	1.58	64.33%	64.58%
	10	25.23	1.57	43.62	2.72	72.89%	73.25%
	30	50.64	3.21	83.23	5.28	64.36%	64.49%
	50	69.01	4.36	113.41	7.20	64.34%	65.14%
	100	106.10	6.61	174.36	10.88	64.34%	64.60%
Type B	2	7.27	0.17	12.37	0.28	70.15%	64.71%
	5	16.22	0.43	26.65	0.70	64.30%	62.79%
	10	26.07	0.69	45.05	1.20	72.80%	73.91%
	30	51.65	1.47	84.87	2.42	64.32%	64.63%
	50	70.17	2.04	115.30	3.36	64.32%	64.71%
	100	107.14	3.09	176.05	5.08	64.32%	64.40%
Type C	2	1.17	0.02	1.92	0.04	64.10%	100.00%
	5	2.60	0.05	4.28	0.09	64.62%	80.00%
	10	4.28	0.09	7.21	0.15	68.46%	66.67%
	30	8.27	0.18	13.58	0.29	64.21%	61.11%
	50	11.20	0.24	18.41	0.40	64.38%	66.67%
	100	16.92	0.36	27.80	0.60	64.30%	66.67%

Table 4.13 Average, Median and Maximum Rates of Bedload Transport for Tributaries (t m s^{-1})

	1:2	1:5	1:10	1:30	1:50	1:100
Average RoBT	6.07	14.52	23.78	48.01	65.50	99.06
Median RoBT	0.05	0.12	0.20	0.40	0.56	0.86
Maximum RoBT	5685	11649	17858	35579	48040	73521
	1:2 CC	1:5 CC	1:10 CC	1:30 CC	1:50 CC	1:100 CC
Average RoBT	9.98	23.86	41.11	78.91	107.65	162.80
Median RoBT	0.08	0.20	0.34	0.67	0.92	1.42
Maximum RoBT	9343	19144	30860	58461	78935	120802
Increase with Climate Change						
Average RoBT	64.40%	64.38%	72.87%	64.35%	64.35%	64.34%
Median RoBT	65.33%	65.12%	73.34%	64.67%	64.63%	64.66%
Maximum RoBT	64.35%	64.34%	72.81%	64.31%	64.31%	64.31%

Key: CC - Climate Change

In Type A river reaches the average and median rate of bedload transport between a 1:2 year flood flow and 1:100 year flood was between 7.42 t m s^{-}1 and 106.1 t m s^{-1}, and 0.41 t m s^{-1}and 6.61 t m s^{-1} respectively. In Type B river reaches the average and median rate of bedload transport between a 1:2 year flood flow and 1:100 year flood was between 7.27 t m s^{-}1 and 107.14 t m s^{-1}, and 0.17 t m s^{-1}and 3.09 t m s^{-1} respectively. In Type C river reaches the average and median rate of bedload transport was between a 1:2 year flood flow and 1:100 year flood was between 1.17 t m s^{-}1 and 16.92 t m s^{-1}, and 0.02 t m s^{-1}and 0.36 t m s^{-1} respectively. The general trend towards a decreasing median rate of bedload transport from Type A to B to C is potentially due to the decreasing slope values associated with each river reach type, meaning there is a drop in the stream power available to transfer sediment.

When the rate of bedload transport was reviewed for the five different typology types used in this study it was found that Type B channels had on average the highest rate of bedload transport (Table 4.14). This was very closely followed by Type A channels which did have a marginally higher rate of bedload transport during a 1:2 year flood. The possible reason for this being that, despite these channel types being characterised by larger bedload grain sizes, these channels tend to occur on steeper slopes providing the channel with more energy to transport sediment. However, the median rate of bedload transport was higher in Type A channels than Type B channels. This suggests that in Type B channels there are a greater number of river reaches with very high rate of bedload transport compared to Type A channels, skewing the data making the average value higher. A potential reason for this could be that plane-bed channels tend to have slightly lower channel gradients than step-pool channels (Montgomery and Buffington, 1997). This would result in Type B channels having a greater range of slope values than other typological groups, and a greater number of high rates of bedload transport away from the median value. The rate of bedload transport in Type D channels remained at less than 0.01 t m s^{-1} until a 1:100 year flood flow under climate change, when the average rate of bedload transport was 0.01 t m s^{-1}. In Type F reaches the rate of bedload transport was never greater than 0.01 t m s^{-1} across all the flood flows reviewed here. The reason for the very low values of the rate of bedload transport in rivers in Type D and Type F river reaches is most likely due to the very low slope, and thus lower stream power values in these reaches.

Climate change predictions of changes in flooding increased the average rate of bedload transport across Type A, Type B and Type C river reaches by between 56 % and 73 %, and median rates of bedload transport between 63 % and 100%. A 1:10 year flood flow with climate change showed the greatest increase in rate of bedload transport over historic flood flows for all reach typologies. The only exception to this was in Type C river reaches where the median rate of bedload transport under climate-change increases by

100% for a 1:2 year flood flow, and 80% for a 1:5 year flood flow, compared to historic flood flow values. This suggests that with climate change, Type C channel reaches will potentially undergo more geomorphic adjustment with 1:2 year and 1:5 year flood flows compared to Type A and Type B reaches.

4.4 DISCUSSION

4.4.1 Model Performance

Model performance was scrutinised by comparing field data with the DRN predictions for channel stability. The model performed well when the 100 field survey sites from the main channel which had been labelled with 'minor instability', 'unstable' or 'highly unstable' were compared with the model predictions under a 1:2 year flood flow. Out of the 100 reaches surveyed, 31 sites were assigned a different stability category compared to 69 which were assigned the same stability category. When the same method was applied on the Girnock Burn, a tributary to the River Dee, a similar result was found, with 29 out of the 43 sites being labelled the same as field observations, and 14 being labelled as different from field observations. The model performed less well in bedrock areas such as the Linn of Dee, the Falls of Feugh and the Linn of Muick Waterfall. In these areas the stream power will be extremely high due to a sharp change in slope, and as a result they were marked as areas of instability by the DRN, and areas of potential channel change. However, these areas are composed of bedrock and thus it is very unlikely rapid changes in channel geometry will occur. Therefore, when using the model this needs to be taken in to consideration, and instability in these areas possibly disregarded as a model error. Alluvial and bedrock situations are obviously fundamentally different. Future work could incorporate screening tools to eliminate bedrock reaches.

During recent high flows on the River Dee due to extreme weather conditions caused by 'Storm Frank' in January 2016, a section of the A93 road between Ballatar and Breamar was destroyed. The river reach where the road was eroded had been identified as an area of channel instability, with a high rate of bedload transport, by the DRN during a 1:100 year flood event. The section of channel close to Abergeldie Castle where the bank was heavily eroded during 'Storm Frank' was identified as an area of high channel instability even at 1:30 year flood. The photographs of these locations and the damage done by the 'Storm Frank' floods, along with the model predictions for these areas for a 1:100 year flood, are shown in Figure 4.11. A 1:100 year flood was shown as it is likely to be the most representative flood size for flooding caused by Storm Frank. The fact that the model correctly predicted these areas as places of channel instability and channel change does help validate the model outputs, and shows it usefulness in predicting areas of channel change and instability.

The overall patterns in channel stability were compared to those generated by SEPA for the River Dee using the ST:REAM Model developed by Parker in 2010. The ST:REAM model calculates the unit bed stream power balance for each reach whereby, in essence, the transport capacity for each reach is compared to the reach above. If the reach above had a greater transport capacity, then the reach was classified as deposition; if the reach above had a lower transport capacity, it was classed as erosion; and if it was the same, the reach was described as balanced. Although the ST:REAM model assesses the differences in the transport capacity between reaches, and the DRN uses the rate of bedload transport to decipher between reaches of minor instability, unstable and high instability, the finding of the two models should both highlight key areas where erosion and sediment transport are high, and thus sections of channel where fluvial hazards will potentially occur.

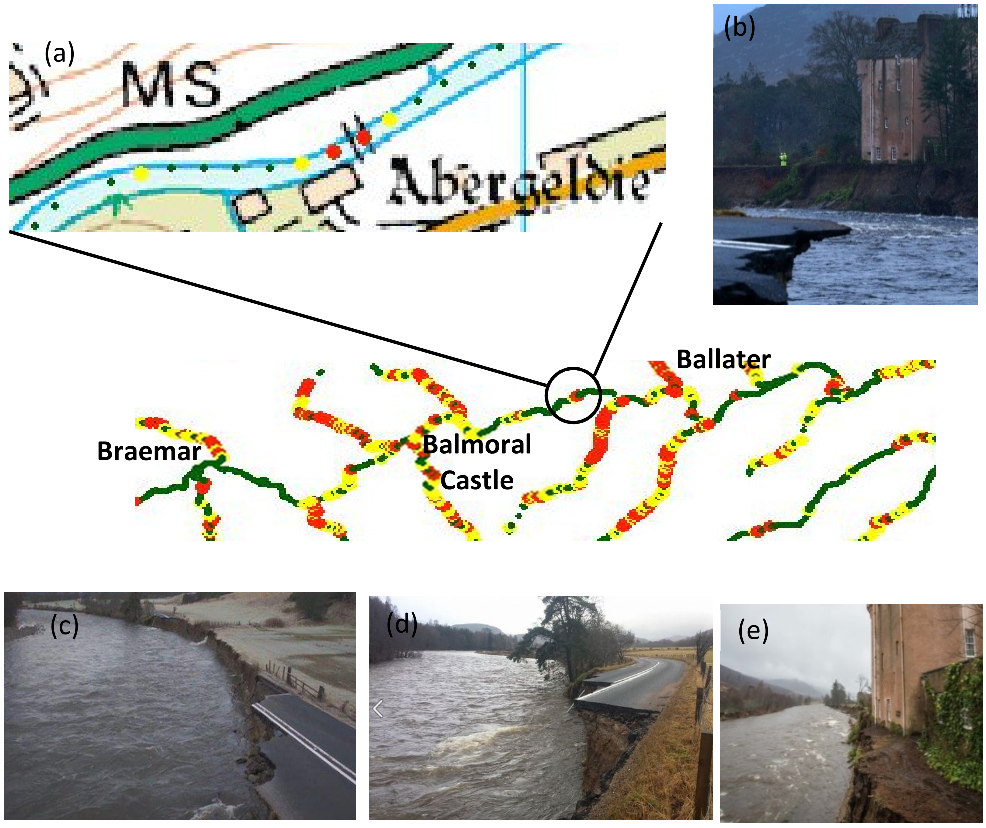


Figure 4.11: Model predictions for a 1:100 year compared to areas of channel adjustment caused by Storm Frank in January 2016. The biggest flood ever recorded on the River Dee, Aberdeenshire over an 85 year period. This figure shows (a) the DRN output for the eroded section of the A93 and Abergeldie Castle (OS, 2002) (b) eroded bank of Abergldie Castle from the A93 (*Source: http://www.smh.com.au/world/uk-floods-threaten-450yearold-castle-near-queens-balmoral-20160105-gm012z.html*), (c) an aerial view of the eroded section of the A93 (*Source: http://www.bbc.co.uk/news/uk-scotland-tayside-central-35206652*), and (d) side view of the eroded section of the A93 (*Source: http://www.bbc.co.uk/news/uk-scotland-35216974*) (e) serve bank erosion at Abergeldie Castle (*Source: https://www.pressandjournal.co.uk/fp/news/aberdeenshire/795497/abergeldie-castle-brink-fearsome-river-dee-closes/*).

A comparison of the model outputs between ST:REAM and the DRN was completed manually. A manual comparison was done due to the differences in how the channel reaches where defined and characterised. Model output comparisons were carried out systematically. Reaches which the model predicted to be highly erosion where compared first, followed by reaches predicted to be depositional and then transfer reaches. Overlying the model outputs of ST:REAM and DRN within ArcMap 10 allowed the output of both models to be compared. Both models suggest higher levels of erosion, or rates of bedload transport, in the tributaries of the River Dee compared to the main channel. A similar agreement in the results of the DRN and ST:REAM Model is found around the Deeside towns of Braemar, Ballatar and Banchory. This degree of similarity is again some sort of overall validation as to the model output. The DRN approach, however, does show a greater heterogeneity throughout the River Dee catchment. For example, the difference in the rate of bedload transport between reaches is captured more easily. This means sudden changes in bedload transport are more easily detected, such as one reach showing 'minor instability' between a series of 'unstable' reaches.

In other locations the models do differ, as in around the town of Aboyne. The DRN suggests that the river east of Aboyne is predominantly a mix of reaches showing 'minor instability' and 'unstable' river reaches, but is generally an area of higher bedload transport rates; whereas the ST:REAM model suggests it is a very stable section of channel, with the rate of bedload transport between reaches being similar. Field observations and surveys would be required to disclose which model is closer to reality in these situations.

It is important to consider that the performance of the model is somewhat limited by the fact that the model is static. This means that it does not take into account the changes in channel depths and channel widths which occur as the volume of water increases due to an increase in flood magnitude. Instead, it is assumed that channel width and channel depth remain constant. To some extent this is a fair assumption, as any water which does not 'fit' into the channel will spill onto the floodplain; however, if morphological adjustments occur in response to the higher flood discharge, then the changes in channel width and depth are not accounted for, and thus neither are potential changes in channel stability and rate of bedload transport. A good example of this would be that, after the

‘Storm Frank’ floods on the River Dee, channel width in certain sections of the channel were significantly increased. Due to the channel being significantly wider, and also possibly due to changes in the channel slope and the bedload grain size in these sections, the transport capacity and morphology of the reach will have been altered. As a result, these changes in the reach’s stability and rate of bedload transport during future flood events will also be altered. It would therefore be recommended that model input values of width and depth, where known, are up-dated regularly to ensure a more accurate model performance.

4.4.2 Model Output

4.4.2.1 Channel Stability and Rate of Bedload Transport

The DRN-based model predicted that the rate of bedload transport, and the likelihood of channel instability, increased as the flood frequency return interval increased from a 1:2 year flood flow to a 1:100 year flood flow. This would be expected, as channel discharge will increase as a river flood return interval increases from a 1:2 year flood to 1:100 year flood, providing the river with more power to erode and transfer sediment. Numerous studies support this finding and have shown that less frequent higher magnitude events provide the river with a greater ability ‘to do work’ leading to increased sediment transport rates, floodplain reworking and destruction of riparian vegetation, leading to significant changes in channel morphology (Foulds et al., 2014; Milan, 2012; Thompson and Croke, 2013). Here, climate change was shown to increase the magnitude of each of the flood return intervals investigated. This would mean that the ability of the river ‘to do work’ at each flood frequency return interval would be greater than in the past under historic flood frequency magnitudes. Thus the river’s ‘response’ to a particular flood magnitude in the future will be different, and potentially more extreme than it has been historically. Previous studies have suggested that increased flood frequencies can lead to channel instability (Werritty and Hoey, 2004), increase in channel sedimentation (Coulthard et al., 2002) and increased channel width (Warner, 1987). However, how the river, and each individual reach, will respond to an increase in flood frequency magnitude will vary depending on certain factors. These include: channel sensitivity to change, sequence of flood events and the effect of climate change on sediment supply to the river (Brunsden and Thornes, 1979; Schumm, 1979; Thorne, 1997; Milan, 2012). In Scotland there are significant numbers of upland catchments which tend to be supply-limited, due to having well-vegetated hill slopes and armoured channel beds. As one of the key drivers in channel morphology, a change in the sediment supply to the channel could cause significant adjustments in channel morphology, as the river adapts to having an increased sediment load (Milan, 2012). Changes in sediment supply can cause changes in bedload grain size (Buffington and Montgomery, 1999), and the ability of different reaches to transport sediment, leading to changes in channel geometry, and in some areas increased channel sedimentation (Lane et al., 2007). However, this level of detail of how each channel may adjust its morphology is beyond the scope of this study, which was catchment and national in geographical scope. Therefore, to investigate how individual reaches will adjust their morphology to the change in flood magnitude, more detailed reach-scale modelling would be recommended.

The results suggest that the rate of bedload transport experienced during a 1:10 year flood under climate change will be the same as a historic 1:30 year flood. A similar pattern was found between a 1:30 year flood under climate change and historic 1:50 flood, and also between a 1:50 year flood under climate change and historic 1:100 year flood. If this occurred, then it would mean that the fluvial hazards and morphological adjustments associated with a 1:10, 1:30 and 1:50 year flood would be much greater than in the past. The impact of the increased magnitude of these flood events on the river channels would vary depending on the geomorphic sensitivity of the river channels to change. This would be affected by factors such as catchment size, local geology, land use, land management and bank strength. Kochel (1998) suggested that floods with a return interval of 1:50 years would be responsible for the modification to the fluvial landscape. This could explain why the greatest increase in channel instability occurred at 1:50 year flood in this study (Table 4.6). If this theory is simplistically applied to the River Dee, the DRN suggests that modification to the river channel under climate change with this size of flood would now occur every 30 years, and that a 1:50 year flood would create much greater landscape modification, as it would be the equivalent of historic 1:100 year levels. Although it is hard to predict what the exact changes will be, the DRN does show that the probable rate of bedload transport through the River Dee is likely to increase significantly in the future, and shows which reaches will potentially have the greatest increase in their rate of bedload transport, and thus a higher likelihood of channel adjustment and channel instability.

When the effect of climate change on the rate of bedload transport for each individual flood frequency return interval was evaluated, it was found that the increase in discharge would increase the rate of bedload transport of the D_{84} of up to 73%. The biggest increase in the rate of bedload transport with climate change was found to be for 1:10 year flood. The reason for this is assumed to be because the predicted increase in a 1:10 year flood was 20%, while all other return intervals were predicted to have only an 18% increase in their flood magnitudes (Kay et al., 2011). This means that the increase in discharge of a 1:10 year flood under a climate change scenario is greater than all the other return intervals investigated here. The 73% increase in the rate of bedload transport found in this study was considered to be a significant increase in the rate of bedload transport. Previous work has shown that sediment transport is very sensitive to flow conditions, and that a flow increase by a factor of 15, can increase bedload transport by a factor of 1000 (Bettes, 2008). This increase in the rate at which bedload is moving through the system will potentially have a knock on effect on the annual sediment budget of the river. However, it should also be considered that in reality, at higher flood magnitudes, a decrease in bedload transport can occur when sediment depletion has occurred (Downs et al., 2016). Thus, future research needs to examine how sediment delivery will respond to increased storminess. This would mean that the rate of bedload transport at higher flood magnitudes may be exaggerated, and the model suggests a 'worst-case scenario' estimate, or rather maximum potential rate of bedload transport for that reach. As the frequency and magnitude of large floods is predicted to increase with climate change, rivers will potentially become more effective conveyors of sediments, something river managers will need to consider when managing river in the future. The model here however, does not consider the sediment supplied from outside the channel boundary. Sediment supply is one of the key variables in determining channel morphology (Thorne et al., 2010). It can alter the sediment grain size distribution, channel roughness and the volume of sediment within a reach. If changes in sediment supply are not matched to transport capacity the channel will adjust through erosion or deposition to try to a re-establish a balance between these two variables (Yager et al., 2012). Future changes in climate will not only potentially alter the transport capacity of the channel, it may also change the sediment supply to the channel. For example, a drier, warmer climate may reduce vegetation cover leading to an increase in sediment supply (Ashmore and Church, 2001). Thus, it is the relationship between these two variables which will ultimately determine how a channel will adjust to future climate change. A channel's optimum capacity to transport sediment of a given size is only achieved if the supply of that sediment calibre is continuous (Hickin, 1995). In reality, many channels are supply-limited meaning that sediment supply to the channel is not continuous and optimum rates of bedload transport are not achieved by the channel (Hickin, 1995). As a result, the rates of bedload predicted through bedload transport equation will overestimate the ability of a channel to transfer sediment. The model here assumes that sediment supply to the channel will remain the same with climate change and that sediment supply to the channel is constant. This is due to there being a lack of data available to be able to qualify the supply of sediment to the river now and any future changes with climate change. The model's inability to account for the volume and calibre of the sediment being supplied to the channel means that the bedload transport rates calculated will, in supply-limited channels such as Type A and B channels, over-estimate the rate at which sediment is transport through the system. This means there is some uncertainty associated with the model results particularly in reaches which are most likely to be supply-limited such as Type A and Type B channels. In more lowland reaches this will be less of an issue as the river is likely to have extensive floodplain development, but in the upper catchment, where hill slope channel coupling is present, this input of sediment is not accounted for by the DRN modelling. However, the omission of sediment supplied from the surrounding catchment being taken into account was deemed to be less important in this model as, unlike other catchment-scale models, the balance between upstream and downstream reaches is not investigated here. Instead, it is the channel's ability to mobilise sediment, and the potential effect of this on channel stability, that is being considered; so, unless sediment-supply from outside the channel boundary significantly changes the sediment grain-size of the reach, information about the sediment supplied to the channel reach is less relevant in outputs generated from this model.

The difference in the rate of bedload transport between different river typologies was reviewed to investigate how bedload transport differed between channel types. Both the median and average values of bedload transport were calculated for each typology. The median value has been used to review the difference between river typologies. This is because it was found that several exceptionally high bedload transport rate values were skewing the average bedload transport values, leading to high-average rates that were not representative of the majority of reaches within each typology.

An example of this can be seen when the average rate of bedload transport between Type A and Type B reaches was investigated. Using the average rate of bedload transport suggested that Type B channels had a higher rate of bedload transport than Type A channels (Table 4.14). The probable reason for this is that the Type B typology is composed of plane-bed and step-pool channels. In the field, step-pool channels tend to have steeper slope values than plane-bed channel reaches (Greig et al., 2006c). As a result, in the model there is likely to be a greater range of bedload transfer rates in Type B channels, with some very high values skewing the average value to be much higher than the median value, compared to Type A which all have very high slope values. To ensure the values that was most 'typical' of that river typology, the median value has been used to look at patterns in the data. This ensures that extremely high values caused by very steep slopes, or very narrow channels, do not skew the patterns and changes in the data.

When the median rate of bedload transport was reviewed in relation to river typology, it was found that it decreased as you went from Type A to Type F, with Type D and Type F typologies not moving more than 0.01 tonnes m s^{-1} of D_{84} bedload particles, even during a 1:100 year flood. In Type A channels (bedrock/cascade) the rate of bedload transport would be expected to be fairly low until a 1:50 or 1:100 year flood flow occurred, providing the channel with enough power to mobilise the larger bedload grain sizes which dominate these reaches, and the smaller sediments which become trapped around them.

However, it has been suggested in the literature (Montgomery and Buffington, 1997) that there is in fact a second lower threshold in which bed mobilisation occurs in low-energy depositional sites during 1:7 year flood flows. Therefore, you would expect there to be a fairly low but steady increase in bedload transport, followed by a significant increase around a 1:10 year flood, and then again at a 1:50 or 1:100 year flood, when larger bedload particles are dislodged. In this study the biggest increase in the median rate of bedload transport was found between a 1:2 year and 1:5 year flood (134%), and between a 1:10 year flood and a 1:30 year flood (104%). This suggests that slightly lower thresholds for bedload mobilisation for Type A reaches in the River Dee, than suggested in the literature (Montgomery and Buffington, 1997). However it should also be considered that in both these instances the increase in flood magnitude has more than doubled which means the shear increase in flow magnitude could explain the greater increase in bedload mobilisation between these return periods and also why the same pattern in seen in Type B and Type C channel typologies.

In Type B (step-pool/plane bed) channels a similar pattern of bedload mobilisation to Type A would be expected, whereby finer sediments in the pools would be transported over the larger bedload particles during more frequent high-flow events, but complete mobilisation of bed and larger clasts would only be expected during large less frequent floods (Montgomery and Buffington, 1997; Schmidt and Ergenzinger, 1992). To gain a fuller understanding of what clast sizes are moving, and what return intervals it would be useful in the future to increase the D_{84} grain size to, and see if that changes the pattern in sediment transport rate, and provides a better picture of when the larger clasts are transported.

In Type C (wandering, plane-riffle, braided) channels, which tend to be more transport-limited than, for example, in step-pool channels, you would expect the rate of bedload transport to increase steadily as the discharge of the river increased with flood magnitude, so it would provide the river with more power to transfer sediment. Some studies have suggested that bedload transport occurs in waves, and the rate of bedload transport can vary depending on antecedent conditions (Montgomery and Buffington, 1997; Passmore and Macklin, 2000; Rice et al., 2009), meaning that significant channel change can occur during moderate flood flows (Fuller et al., 2003). These patterns are picked up in this study and, like the Type A and Type B channels, there is a significant jump between a 1:2 year flood and a1:5 year flood, and then also between a 1:10 year flood and a 1:30 year flood, due to the significant change in discharge between these flood flows. When these patterns were compared to what would occur under a climate change scenario, a similar pattern occurred; however, the rate of at which sediment was transported increased by between 56 and 100 per cent. However, this assumes that the increased discharge can be accommodated within the channel's current geometry, but as discussed further below this may not be the case. Even taking this into account, the model provides an indication of the channel's potential to transfer sediment, and thus the increased possibility for the channel to undergo morphological adjustment. Additionally, it should be considered that over time river channels are likely to adjust to the 'new' discharge associated with the different flood return intervals, meaning long-term it is likely that the river will develop a morphology that allows it to convey larger volumes of water and sediment, and re-establishes a dynamic equilibrium, and thus stability.

The possible reason for a reduction in the rate of bedload transport as you go from a Type A to Type F channel could be that slope is one of the early parameters used to define the river typology within the model. This means that as you go from channel typology Type

A to F the slope values associated with each river typology will decrease, meaning the channel will have less power to transfer sediment. Conversely, the sediment grain size also decreases as you go from channel typology A to F, meaning less power is required to move the D_{84}. Studies (Sambrook Smith and Ferguson, 1995; Dade and Friend, 1998) have suggested a link between sediment size and channel slope in which the mode of sediment transport transitions from bedload-dominant, to suspension-dominant. Suspension-dominated reaches tended to be where slopes had values of 0.0001 or flatter. In this study, Type D and Type F reaches all have slope values flatter than 0.0008; suggesting, based on the findings of Dade and Friend (1998), that they would be suspension-dominated reaches. This could mean that these reaches only tend to transport suspended material, and that the D_{84} of 25mm and 50mm for Type F and Type D reaches are too high to be moved even under high flood flow conditions. When the sensitivity of different channel types to adjustment was evaluated in New Zealand (Reid and Brierley, 2015), it was found that active (Type D) and passive (Type F) meandering reaches underwent minimal change, whereas the wandering gravel-bed reaches (Type C) had moderate sensitivity to change and were more responsive to larger flood flows; a finding which is supported by the results of this study.

Spatially it was found that the rate the bedload transport and thus channel instability was predicted to occur primarily within the tributaries of the catchment, rather than within the main channel, with only 0.91% of main channel reaches becoming unstable (‘unstable’ and ‘highly unstable’ reaches), compared to 1.46% of tributary reaches for a 1:2 year flood, increasing to 3.09% and 9.94% respectively for a 1:100 year flood (Table 4.9 and 4.10). The small catchment size of the tributaries, and their valley confinement, means they tend to be geomorphologically more sensitive, due to having higher slopes and increased flood depths compared to the main channel. This means that the tributaries can have flashy regimes, resulting in very high flood peaks compared to the median flow of the channel, resulting in high levels of bedload transport and channel instability (Knighton, 1998). The higher slope values and narrower channel widths within the tributary reaches would also mean they would have higher stream powers, making them more sensitive to changes in discharge than those reaches with lower slopes and wider channels. Reducing channel width has been shown to increase transport capacity; for example, when looking at different river practices Davies and McSaveney (2006) showed that a narrowing of channel width increased the river's ability to transfer sediment. When these finding are applied to the results in this study, it therefore would make sense that narrower, steeper tributaries would have a greater potential for instability than the wider, shallower main channel, at the same flood return interval. Furthermore, when the timing of sediment transfer within tributaries was compared to the main channel, within a 72km^2 catchment in the Yorkshire Dales, it was found that sediment transfer occurred much more frequently at lower flood magnitudes in the tributaries (Reid et al., 2007). The reason for this being, the increased sediment delivery from the surrounding catchment and channel discharge, as smaller steeper tributaries were more effective at moving sediment, especially when it was generated quickly from the catchment (Reid et al., 2007). Previous work examining the timing, nature and magnitude of flood events in the Tyne basin, northern England showed that the response of tributaries and the main channel differs in relation to different flood frequency patterns (Rumsby and Macklin, 1994). Moderate sized floods (1:5 to 1:20 year floods) were found to cause increased lateral migration and sediment transfer in upland tributaries whereas large floods (> 1:20 year floods) caused channel incision across the Tyne catchment (Ramsby and Macklin, 1994). A similar pattern was seen in this study whereby the percentage increase in the number of unstable reaches was much higher in the main channel compared to the tributaries at higher large flood return intervals (> 1:10). This further suggests that changes in the tributaries will occur more rapidly as they are impacted more by lower magnitude, higher frequency flood events compared to the main channel where higher magnitude, lower frequency floods are required before more significant changes in channel stability and rates of bedload transport will occur.

Along the main channel, instability was found to occur primarily at tributary junctions and at meander bends. Channel instability occurring at tributary junctions would be expected even at fairly frequent flood intervals, as within the model they will represent areas of sudden change within the river system, where discharge suddenly increases, and in reality they mark locations where there is often a sharp increase in median bedload size, and in discharge and slope (Ferguson et al., 2006; Rice et al., 2011). Without these stepped inputs of increased sediment and discharge, a river would progressively change as it flowed downstream, with discharge and channel-width increasing, and slope and grain size diameter decreasing (Rice, 1998). The sudden change in channel-forming properties (discharge, sediment supply and sediment grain size) at tributary junctions can have a marked effect on channel morphology and channel stability, and river ecology. How the river responds to these changes depends on a number of other factors, such as planform geometry (confluence angle, and planform shape upstream and downstream), ratio of main channel discharge to tributary discharge, difference in bed height between the main channel and the tributary channel, and differences in flow-density between the main channel and the tributary channel (Ferguson et al., 2006). The larger the incoming tributary, the greater the inputs of water and sediment into the main channel, and the greater the change in channel structure at the confluence (Benda et al., 2004). Therefore, higher discharges brought with flood flows would increase the volume of coarse sediment and water moving into the main channel, resulting in higher levels of channel instability and potential shifts in channel morphology. Furthermore, as the model suggests that the tributaries will be transporting more material at lower flows than the main channel in the future leading to an increased aggradation at these sites, a coursing of the river bed and with this increased channel instability (Rice et al., 2008). Previous studies in the Tyne highlighted this (Rumsby and Macklin, 1994). Rumsby and Macklin (1994) found that increased rates of sediment delivery from the tributaries into the main channel lead to very high rates of in-channel sedimentation in the middle and lower catchment of the Tyne. However, due to the complex processes occurring at tributary junctions, more detailed modelling work would be recommended to fully understand how climate change would influence their channel morphology.

4.4.3 Model Uncertainty

4.4.3.1 Discharge

The discharge value for each 50 metre reach for each flood return interval was generated using the CEH flow accumulation grids. These grids make the assumption that the channel discharge will increase linearly as the river travels downstream, which under low flows or normal flow conditions would be a reasonable assumption. The assumption made here is that during flood flows the same linear increase in discharge applies, and that the channel can hold and convey the water associated with this increase in discharge. Thus it is assumed that as discharge increases, so does the channel's ability to erode and transfer sediment, and therefore so does the river's ability to mobilise the D_{84} sediments within a reach. However, with flood flows often the extra water will be not be accommodated by the channel, and the excess water will flow onto the floodplain, and thus not be available to transport sediment, leading to the model over-predicting the stream power of a reach. Or, the river may erode the channel, making it wider, changing its geometry, and thus changing its stream power and its ability to transfer sediment. Finally, the model doesn't take into account the timing between floods, and therefore assumes the ease at which bedload is moved is the same from flood to flood. In reality, bedload is easier to move if there is a smaller gap between floods than if there is longer one, as the bedload has had longer to consolidate (Reid et al., 1985). When (Downs et al., 2016) compared the bedload transfer of two floods of similar discharges on the River Avon in Devon, it was found that more bedload transfer occurred after a large flood event. This was attributed to a greater volume of sediment being delivered from the surrounding catchment, and thus highlights the importance of antecedent conditions when looking at the ability of rivers to transport sediment (Downs et al., 2016; Lenzi et al., 2004; Turowski and Rickenmann, 2009). Additionally, ideally the duration of the flood would also be considered because the longer the river has the power to erode and transfer sediment, the greater the potentially change in channel morphology. There is also the assumption that a whole reach is transporting sediment at the same rate. In reality, the rate of bedload transport will vary across the reach (Raven et al., 2011). When sediment sensor plates were used on the River Avon, it was found that bedload transport was asymmetrical within a reach, and also varied with discharge (Downs et al., 2016). To model the rate of bedload transport at this level of detail at the catchment and national scale would require a large amount of computing power and a very highly trained geomorphologist, and thus it was concluded that modelling to this level of detail was more suited to modelling reach scale sediment transport. The model's main aim is to predict changes in the rate of bedload transport, and highlight areas of potential channel instability, which an increase in discharge is well recognised to be associated with (Werrity, 1997). It is therefore assumed that the outputs from the model will still provide a good screening tool for predicting the rate of bedload transport and potential areas of channel instability at 50 metre intervals throughout the River Dee catchment with changing flood flow magnitudes.

4.4.3.2 Channel Geometry

Spatially derived channel widths, and channel depth values, which provide an indication of channel geometry can result in errors leading to uncertainty within the model outputs. Defining channel width is a fundamental geomorphological problem in itself, as it can often be slightly subjective as to where an individual takes channel width from, especially in areas were gravel bars are present. Here it was found that the modelled channel width was narrower than that measured in the field, but the pattern of increasing and decreasing channel widths between sites was similar. The biggest discrepancies in channel width were found in the head waters, where channel width had been defaulted to 1 metre, and in areas where there were large gravel bars, and evidence of channel-shifting and avulsion. A similar pattern was found by Baker (2008) when comparing field-measured channel width to OS MasterMap channel widths along the River Alne in Warwickshire. Baker reported that field measurements of channel width were greater than those predicted using OS MasterMap data, with the biggest difference being in the headwaters. As a result, it is likely that the model will slightly over-estimate the stream power of each 50metre reach, leading to a slightly elevated rate of bedload transport.

The DRN can only work in straight lines, meaning meanders are defined as a series of zig zags. As a result, in these sections the channel centreline is not in the middle of the channel or even in the channel, so at these points the channel width and depth measurements have an increased likelihood of being inaccurate.

Channel depth is likely to be overestimated in areas where the depth value is not taken from the channel edge but instead taken from further up the floodplain, or underestimated if the channel edge is taken from the middle of the channel rather than the bank edge. The ability of the model to predict very small difference in channel depth, or the depth of narrow channels, is reduced, as NEXTMap DEM only has a 5metre resolution. This means that sections of channel which are all on the same 5 metre grid square will have a channel depth of close to zero. In many cases this would be found to lead to over-estimates in the rate of bedload transport achieved by each reach. However, as the availability and resolution of spatial data improves, the ability to more accurately predict channel depth will improve, leading to a more accurate model output.

4.4.3.3 Channel Typology

Although the use of slope, geology, sinuosity and valley confinement have been shown to be a sound basis for automating the predicted channel typology, other factors which are also important in determining channel morphology, such as boundary strength, riparian vegetation and bed material size, have not been considered in the development of river typology. As yet, the acquisition of this data spatially at the catchment or national scale is still work in progress; and collecting the required field data would be an extremely time-consuming method, and therefore would diminish the model's usefulness in screening for channel instability and change. It would, however, be recommended to evaluate how these factors influence channel morphology, and the merits of including them within the decision-tree for defining channel morphology. The addition of parameters such as riparian vegetation, or land use, could be used to highlight the change in channel typology in different areas with changes in land management. At present, though, the model does provide a logical and field-tested channel typology, which can give managers a useful insight into different river reaches at both the national and catchment scale, without the need to leave their desk. The ability for river managers to do this means better decisions can be made on where or what sort of management options may be appropriate, before doing can field-based surveys.

4.4.3.4 Bedload Grain Size and Channel Stability

The assumption is made in this study that a river reach will become unstable when there is enough power to move over 28 t m/s^{-1} of the D_{84} grains. However, some reaches will become unstable when smaller grain sizes are transported, and some will require bigger pebbles and more bedload to be mobilised before the reach becomes unstable, depending on the channel's sensitivity to change (Andrews, 1983; Torizzo and Pitlick, 2004). Additionally, in reaches which have been partially modified, their grain size distribution may be different from more natural, relatively unmodified reaches, resulting in the rate of bedload transport, and the projected impact on channel stability in these reaches, being inaccurate. Morphological channel adjustment if often accepted as occurring with flood flows that exceed bankfull (Andrews, 1980; Biedenharn et al., 1999; Knighton, 1998); it was assumed that the bedload particle selected had to be one that was most likely to be mobilised at a flow that exceed bankfull. As previous studies have demonstrated that D_{50} is regularly mobilised at flows less than bankfull, but the D_{84} is more frequently moved at flows in excess of bankfull discharge (Heitmuller, 2011). The decision was therefore taken to use the D_{84}, as it provided the best indicator of potential channel change and instability.

4.4.3.5 Bedload Transport Formulae

As stated by Gomez and Church (1989), ultimately no bedload transport formula will be completely accurate in predicting bedload transport in gravel bed rivers. General sediment transport models will overestimate the rate of bedload transport because they fail to take account of surface coarsening and variations in the rate of sediment supply (Hicks and Gomez, 2003). As a result, there will always be a level of uncertainty associated with the outcome of any bedload transport formulae model. The best way to reduce this uncertainty is to select a bedload transport equation which best represents the sediment size distribution of the channel being investigated. For example, stochastic approaches such as that used by Einstein and Barbarossa (1952) tends to work best in sand-bed channels with uniform sediment and flow conditions and overestimates bedload transport in gravel-bed rivers; whereas stream discharge bedload formulae such as Meyer-Peter (Meyer-Peter et al., 1934) tends to work better in rivers with beds composed of small gravels (Gomez and Church 1989). As the bed of Scottish rivers are predominately composed of sediments ranging in size from course sand to large boulders, these bedload transport formulae where considered inappropriate. Meanwhile, Parker et al.'s, 1982 bedload formulae which is based around the principles of shear stress or tractive forces i.e. the difference between the force applied to the river bed versus the force required for a particle of given size to move (Hicks and Gomez, 2005) has been designed using a natural mix of sediment sizes. However, Parker et al.'s (1982) formulae requires a reference transport rate to be generated based on the proportion of gravel and sand present in each reach (Wilcock, 2001a). To estimate this for each 50m reach across the catchment of the River Dee would have created huge uncertainty in the model output and, as a result, this bedload formulae was not selected. Bagnold's (1980) stream power based equation relates the rate at which sediment is transported to the rate of energy expenditure to the channel and can theoretically be used for any grain size. Furthermore, this equation has been used with success by the Environment Agency (Thorne et al., 2010) and Gomez and Church (1989) concluded that Bagnold gave the most 'reasonable results' for the movement for a range of bedload sizes when they reviewed the effectiveness of 10 different bedload transport formulae. Due to the ease and availability of the necessary data needed for calculating the rate of bedload transport using stream power and its ability to deal with a range of bedload sizes resulted in the Bagnold equation being used here. Although this formula was originally developed for sand channels, its underlying theory is still relevant to gravel bed channels (Gomez and Church, 1989). This is why it has been selected here. In using the Bagnold equation it has been assumed i) that there is a constant supply of sediment to the channel, ii) a Shield's number of 0.04 is appropriate iii) channels with a higher sediment load have a wider channel iv) bedload transport is uniform across the entire river bed (Gomez and Church, 1989; Thorne et al., 2010; Gomez, 2006). These assumptions mean that the rates of bedload transport reported here are likely to be an overestimate of reality. This is because it is unlikely that the rate of bedload transport will be uniform across the channel. Instead it will most likely be greatest along the thalweg and decrease as you more away from the thalweg towards the banks. In instances where sediment supply is limited, the bedload transport rate may be overestimated due there not being enough sediment of a desired size to transport. Despite these assumptions the model will provide a good estimate of the relationship between different reaches and the relevant differences between reaches as well as highlight areas where channel instability and increased erosion are most likely to occur. Future work could consider using Gomez's (2006) modified Bagnold formulae. This formula incorporates a regression relationship into Bagnold's original formulae to estimates the average rate of bedload transport in gravel bed rivers to within ±10% (Gomez, 2006).

4.4.4 Model Application

The understanding of areas of potential morphological channel changes, and at what flows and where these changes may occur within a catchment, is important for ecosystem services, flood risk, sediment management and channel restoration. The ability of the DRN Model to provide an indication of areas of high and low bedload transport rates means it can be used as tool to assist management decisions in the areas mentioned above. In areas where sediment removal is undertaken for flood risk or quarried for use in footpaths the DRN could be used to give an indication of how quickly this sediment will return and ensure that amount removed does not destabilise the river. The model could further help with legislative tasks such as the Controlled Activities Regulations 2011 (CAR) and the Water Framework Directive (WFD) requirements. For example, if an application comes to build a new bridge the DRN could be consulted to assess the risk of structure being undermined by erosion during high flow events and with future events under climate change. Being able to know the level of risk could influence and design and location of the bridge to ensure it will not be damaged in future high flow events. Previously, when investigating channel stability, sediment and flood related management issues, often the first step would be to carry out very time consuming and labour-intensive Catchment Baseline Surveys around the 'problem' area. The DRN provides river managers with the ability to assess changes in stream power, and rate of bedload transport rate, at different flood flows, before venturing into the field. The ability to do this allows managers to gain some perspective on what is happening, before carrying out field survey work, and also to ensure a more targeted approach to field surveys by ensuring that the correct data is collected from the correct locations within the catchment. This saves time and money, and gives managers some insight into what is happening, not only within the 'problem', area but also in the reaches upstream and downstream. The capability to see how reach stability and rate of bedload transport changes with differing flood magnitudes, and potentially with predicted climatic changes, allows river managers to see how the reaches above and below, for example, a restored reach may be affected by climate change, and take that into consideration in the design phase of the project.

As the resolution of the DRN is at 50m intervals there is a greater probability that sudden changes in channel width, stream power or slope will be detected, potentially providing a greater insight into why certain management issues are occurring. In models where the reach length is significantly greater, for example 500m, parameters such as channel width, sinuosity and slope will be averaged-out over a larger section of channel, possibly leading to a dampening effect of potentially significant sudden changes within the channel. The DRN also has the advantage that it can be used by anyone with a small amount of GIS knowledge, making it accessible to people lacking advanced modelling skills, and lacking hydrological and geomorphological knowledge of the catchment under investigation. Additionally, if the correct spatial data is available, it could also be possible to use the same method to undertake some historical analysis. This would be done by using an old digital-elevation model of an area, and the corresponding OS Master Map data, to recreate the DRN, and compare the difference in channel typology and rate of bedload transport. However, realistically, unless the data resolution is very high or consistent between the two model outputs being compared, this may not provide an accurate representation of the difference in channel stability over time.

There are limitations with using the DRN Model alone to make management decisions, due to the levels of uncertainty with some of the parameters, the assumptions made when developing the model, and also the requirement for more data for model validation. It would therefore would be advised that the DRN Model was used more as a screening tool, alongside field surveys, and alongside detailed sediment and hydraulic modelling, to assist in making management decisions. As improvements in spatial data and computing power advance, it would be expected that the accuracy of model predictions would improve, increasing the DRN ability to assist in river management decisions. Further work looking at incorporating the resisting forces of the channel, such as bank erosion, would aid in better prediction of channel stability and resilience to change. Currently, channel typology is used as an indication of bank and bed strength (Greig et al., 2006c). Additionally, it would also be useful to automate the model to look at changes in the rate of bedload transport from reach to reach. This would help to better predict areas where sedimentation issues may be present, which could lead to flood risk through floodplain inundation; especially, as the significance of in-channel sedimentation on flood risk and floodplain inundation have been highlighted within the literature (Lane and Richards, 1997). However, despite these limitations, the DRN Model shows what can be achieved with the spatial data available at present, and highlights the knowledge that can be gained about a river catchment without leaving your desk.

4.5 CONCLUSION

The accurate modelling of channel change, channel instability and bedload transport at the catchment, regional and national scale is a significant and continual challenge for fluvial geomorphologists. The continued advances and improvements in the resolution of spatial data have helped to make progress in these areas more achievable. However, when modelling at this scale, there needs to be an acceptance of what that can actually be achieved using spatial data, and the accuracy that can be achieved using this data. Ultimately, there is always going to be uncertainty when modelling rivers at this scale, due the simplifications and assumptions that need to be made when creating the models at larger scales, many of which have been outlined above. As detailed by Vocal Ferencevic and Ashmore, (2012), a GIS-based stream power driven approach, as has been used here, does provide effective means of looking at geomorphic change at the catchment scale, as it is physically based, objective and time-efficient. Previous studies have also shown that the use of stream power within models is an effective means of looking at geomorphic adjustment at the catchment scale, and have proved it to be extremely useful in making management decisions, and for predicting areas of potential fluvial hazards (Parker et al., 2015; Thompson and Croke, 2008). Vocal Ferencevic and Ashmore, (2012) highlighted this when the reach with the highest stream power values across the catchment under investigation underwent the greatest amount of geomorphic adjustment during flood conditions. This was further shown again in this study, when the DRN accurately predicted areas of channel instability during 'Storm Frank'. Models such as the DRN model discussed here provide an indication of the current status of the science, in terms of using spatial data to predict channel instability and bedload transport, and in highlighting the advancements that can be made with improvements in spatial data and computing power. Additionally, models such as the DRN provide managers with a user-friendly interface to investigate changes in channel stability and the impact of different flood flows, and also the impact of climate change on rivers, as long as assumptions and simplifications made within the model are borne in mind. The ability of river managers to use the DRN, along with more targeted field surveys, as well as more detailed hydraulically detailed and sediment-routing models will aid more time-efficient and better management decisions in the future.

4.6 SUMMARY

- The use of SEPA's DRN to predict changes in channel stability and the rate of bedload transport, with changing flood return intervals, and with changing flood return intervals under climate change, has been investigated.
- It has been shown that the DRN could be a useful screening tool for looking at changes in channel stability and bedload transport at the catchment and potentially national scale, but it would be advisable to look at more detailed reach scale channel changes, and more detailed sediment-routing models.
- The DRN model did accurately predict areas of channel instability during 'Storm Frank' in January 2016.
- The DRN Model predictions suggest that within the River Dee channel instability occurs primarily at tributary junctions and within the tributaries. The catchment as a whole was predicted to remain fairly stable up to a 1:100 year flood. Less than 20% of river reaches were predicted to show signs of channel instability at this flood magnitude.
- Under a climate change scenario, the model predictions suggested that a channel instability of a 1:5 year flood would mirror an historic 1:10 year flood level, a 1:30 year flood would mirror an historic 1:50 year flood level, and a 1:50 year flood would mirror an historic 1:100 year flood. The rate of bedload transport by the river was suggested to increase by up to 72 % for each flood return interval investigated.

CHAPTER 5

Investigating the Key Parameters and Defence Mechanisms used by the Freshwater Pearl Mussels to Avoid Entrainment

5.1 INTRODUCTION

Current predictions on future climate change for the UK suggest that both flood magnitude and frequency are likely to increase. Similar findings have been found in this study in chapter 2 which showed that the frequency of winter high flows is likely to increase in the future with climate change. Furthermore, in chapter 4 it was shown that the rate of bedload transport and likelihood of channel instability for a given flood return interval would increase with climate change. These changes in the flow and sediment regime of rivers are likely to have a significant effect on lotic species as they will have to withstand increased shear stresses and habitat disturbance as well as having shorter recovery periods between high flow events. Therefore, to better manage vulnerable aquatic species with climate change, river managers need to gain a greater understanding of the consequences on high magnitude flood events on riverine ecology. This is particularly important for benthic organisms, as large floods can displace populations to unfavourable habitats, scour favourable habitat reducing habitat availability, and hence negatively affect recruitment and significantly reduce population numbers (Vannote and Minshall, 1982; Hastie et al., 2001; Bunn and Arthington, 2002; Morales et al., 2006). The critically endangered freshwater pearl mussel (*Margaritifera margaritifera*) is one benthic species which faces an uncertain future under future climate change predictions (Hastie et al., 2003). Not only will increased high flows potentially reduce suitable habitats by scouring the rivers, but increased water temperature and summer droughts may affect recruitment (Metcalf, 1983; Hastie et al., 2003). As 50% of the world's recruiting populations reside in Scottish rivers, where future climate change scenarios suggest increased winter wetness leading to higher flood magnitudes and frequencies (Werritty, 2002; Prudhomme et al., 2003; Cameron, 2000; 2006) it is imperative river managers gain a fuller understanding of the effect of high flows on freshwater pearl mussels. Despite the status of freshwater pearl mussel as an endangered species, along with a substantial knowledge of its habitats requirements (Hastie et al., 2000; 2003; Geist and Auerswalds, 2007; Degerman et al., 2009; Cosgrove et al., 2014), and suggested conservation and management strategies (Young and Williams, 1983; Bauer, 1988; Beasley and Roberts, 1999; Cosgrove et al., and Hastie et al., 2001) little is known about how the species responds to flood events. A notable exception is the work of Hastie et al., (2001) who examined the response of a freshwater pearl mussel population to a 1:100 year flood event on the River Kerry, Scotland. Hastie et al. (2001) concluded that juvenile (individuals less than 10 years of age) mortality within the population was between 4-8% (50,000 individuals). The results from this study highlighted the importance of bed stability (bedload structure and size) in allowing freshwater pearl mussels to avoid entrainment during high flows. Mussel beds in the more stable river were showed the smallest reduction in population size (<3%) post flood event (Hastie et al., 2001). A conceptual model showing the relationship between bed structure and high flows events on the occurrence of mussel entrainment is shown in Figure 5.1.

The high mussel mortality rates associated with high flow events is worrying if current climate change scenarios predictions for Scotland suggesting a 1:100 flood may become a near 1:50 year flood are correct (Cameron, 2006). Under this scenario mass mortality in pearl mussel populations, as seen in the River Kerry, may become more frequent. The work by Hastie et al. (2001) along with that related to North American mussel species (Vannote and Minshall, 1982; di Maio and Corkum, 1995) have shown mussels are particularly vulnerable to high flows, from entrainment and scour of habitat. Their fate can be shell damage, deposition and desiccation on river margins and transfer to unfavourable habitat locations. Moorkens and Killeen (2014) have shown that pearl mussels can live happily at relatively high near-bed velocities of 0.3 ms^{-1}. However, at present the water velocities needed to entrain freshwater pearl mussels and the factors controlling their displacement and transport are poorly quantified and understood. This paper presents a method and findings which could be developed to measure the water velocities required and factors affecting entrainment of freshwater pearl mussels and other mussel populations during high flow velocities. The specific aims of the work were to: (i) measure critical near-bed water velocities needed to entrain freshwater pearl mussel on simple beds, (ii) assess the effect of bed substrate particle size and substrate heterogeneity on entrainment and (iii) determine the best mechanisms which can be used by freshwater pearl mussels to resist entrainment.

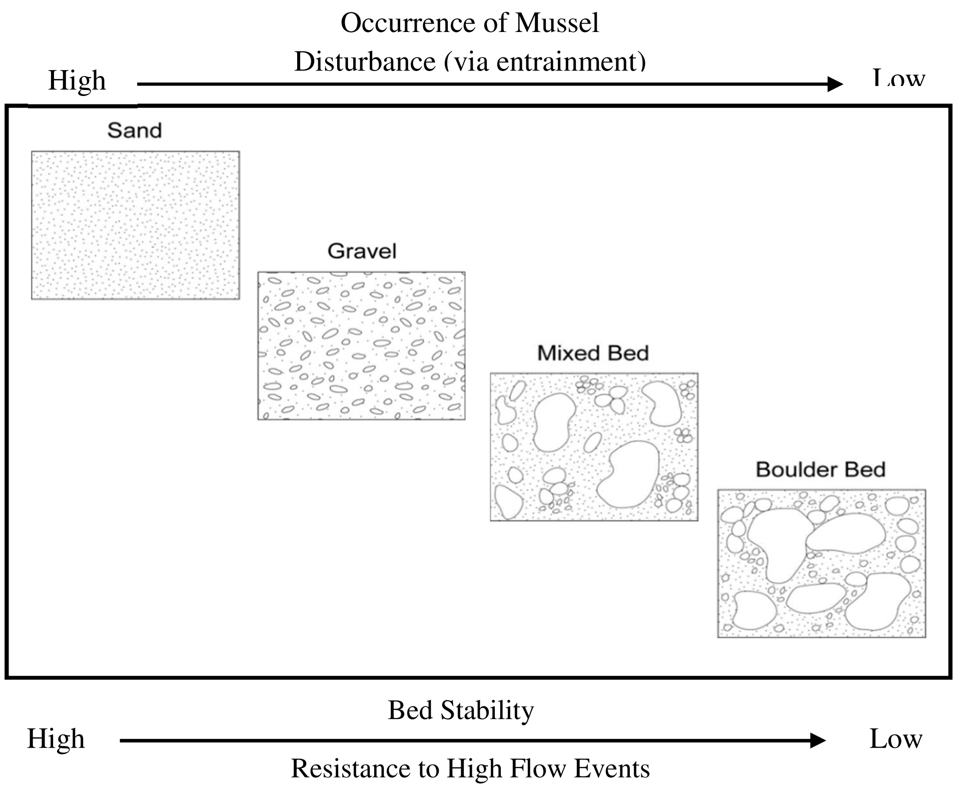


Figure 5.1: Conceptual diagram of the link between mussel entrainment, bed sediment size and structure and high flow events.

5.2 METHODS

5.2.1 Field survey

Field surveys of freshwater pearl mussel habitat types were carried out on two Scottish rivers known to be populated with the species. Locations known to be inhabited by over 100 freshwater pearl mussels were visited during low flows to establish the different physical habitats types that freshwater pearl mussels occupy. At each site a Wolman Pebble count of 100 clasts was conducted and the river bed was systematically surveyed using a bathyscope glass bucket to locate the mussels. When a mussel or cluster of mussels was located the following parameters were measured for each mussel: cluster-size, water depth, burial depth, and foot presence, in addition to the length, width and weight of the mussels. Cluster size was defined as the number of mussels living grouped closely together (less than 5 centimetres apart) on the river bed. When mussels were pulled from the river bed the point marking where the shell was submerged in the river bed (i.e. average bed elevation surrounding the mussel) was noted. The exposed section was then measured using a pair of callipers. The callipers were used to measure the total length of the mussel, and mussel width. Portable electric scales were used to measure the weight of the mussels to one decimal place. A mussel's foot (an external muscle projecting from the base of the mussel, the beats of which allow the mussel to move) was deemed as present if when pulled out the river bed it could be seen protruding from the base of the mussel shell. An underwater camera was used to photograph the mussels surveyed and the fabric of the river bed they were located in, to aid replication of the bed environment within the flume.

5.2.2 Flume environment

An indoor concrete recirculating flume, with viewing chamber, was used to replicate high flow conditions (Figure 5.2). The viewing chamber contained a video camera and all flume runs were filmed. An electrically-driven propeller pump allowed the flow to be stepped up in ten increments (low flow to high flow) with water velocities over 2 m s^{-1} being achieved at level 10. On one of the straight sections of the flume a 1.0 x 0.58 m area was set out for substrate bed material placement and, for each run scenario, was replicated to match conditions observed in the field.

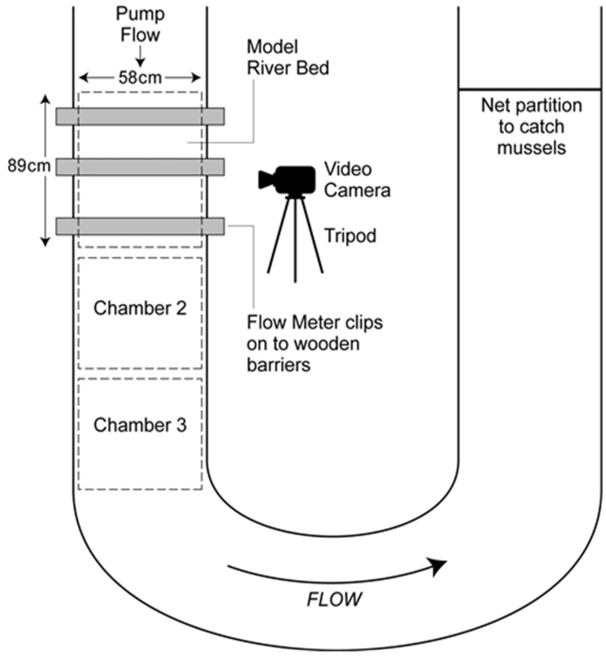


Figure 5.2: Plan view of flume set up

Four different substrate types (Figure 5.3) were replicated, namely sand-bed, gravel-bed, mixed gravel/cobble bed and cobble/boulder bed. The substrate used was a mix of river pebbles, cobble and boulders taken from a local river, and sand and gravels taken from the shores of Loch Lomond. The pebbles, cobbles and boulders used were selected to provide good representation of the different types of substrate found on the natural river bed. Sand from Loch Lomond shore was sieved through a 2 mm sieve. Photographs of the substrate, in the presence of mussels, taken during the field surveys were used to aid with the placement and construction of the substrate within the flume. Once the substrate had been placed in the flume 16 individually numbered replica mussels were placed at varying burial depths and orientations.

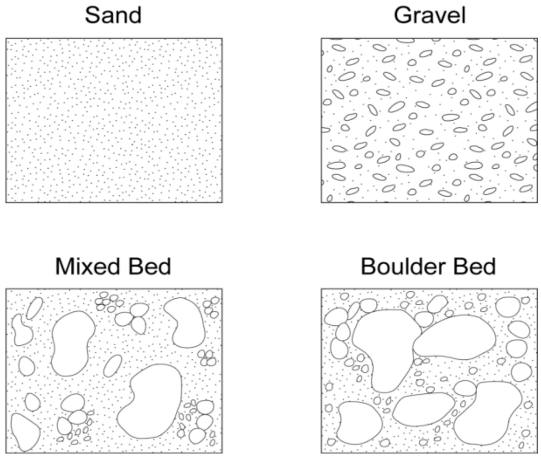


Figure 5.3: Different bed substrates used within the flume

Mussel burial depth was taken as a percentage of the replica mussels shell length and varied between 40%, 60% and 80%. These values were chosen as the average burial depth in the field across the mussels surveyed was approximately 60% and then 20% either side of this value as over 80% of the mussels surveyed fell within that range. All substrate/mussel permutations were covered with 0.3 to 0.35 metres of water. The pump was then turned on and flows left running for 45 seconds before velocity readings and observations of mussel movement were made. Velocity readings were taken using a FLO-MATE 2000 portable electromagnetic velocity metre. This protocol was repeated for the 1 to 10 flow increments or until all mussels had been entrained. Five of the flume run permutations were repeated to ensure that there were no large differences in the average and median entrainment velocities of the mussels when the runs were repeated. This was done for two sand runs: 0 degrees orientation and 40% burial depth, 0 degrees orientation and 60% burial depth, and for gravel, mixed and boulder beds at 0 degrees orientation and 40% burial depth. A Mann-Whitney test was done to confirm that there was no significant difference between the repeated runs (Table 5.1). As no significant difference was found only one run was done for all other flume run permutations due to time restraints.

Table 5.1: A statistical analysis of multiple runs of the flume to assess water velocity repeatability between runs. Number is brackets is replicate number.

Run	Average m/s-1	Median m/s-1	W	P-value
Sand 0, 40 (1)	0.9	0.9	197	0.1199
Sand 0, 40 (2)	0.86	0.9		
Sand 0, 60 (1)	0.87	0.85	125.5	0.5201
Sand 0, 60 (2)	0.89	0.9		
Gravel 0, 60 (1)	0.93	0.9	146	0.9707
Gravel 0, 60 (2)	0.94	0.9		
Mixed Bed 0, 60 (1)	1.13	1	106.5	0.8155
Mixed Bed 0, 60 (2)	1.1	1.1		
Boulder 0, 60 (1)	1.5	1.5	45.5	0.6505
Boulder 0, 60 (2)	1.47	1.5		

5.2.3 Mussel morphology

Replica freshwater pearl mussels were used consisting of dead mussel shells filled with plasticine or gravels. To gain the appropriate weight the length and width of each mussel shell was measured and then compared to the length and width of mussels surveyed in the field. The mussel was then weighted down with plasticine until it weighed the same as a field mussel with a similar length to width ratio. Shell length, shell curvature and mussel weight were between 73 mm and 116 mm, 0 mm and 4 mm and 26.8 g and 125.2 g respectively. In order to try mimic the mussel foot 50% of the mussels had gravel placed in the bottom of their shell to the desired mussel weight rather than plasticine around the umbo. As the mussels with gravel were heavy at the bottom it meant they stayed anchored to the flume river bed thus to some extent simulating the suggested role that the foot plays in anchoring the mussel to the river bed in the wild. For the purposes of this study only adult mussel shells were used. An adult mussel was deemed to be one greater than 65mm in length (Hastie, 2011).

5.2.4 Flow measurement and mussel entrainment observations

Near-bed water velocity readings were taken at mussel shell apex height at 8 fixed locations laterally and longitudinally, in the zones of mussel placement within the area of flume bed substrate. This was repeated for each incremental increase in flow. Each reading was taken at 5 second intervals for 30 seconds and then averaged. Time and mussel identification number was recorded at the time of entrainment. This was done manually and if a number of mussels moved simultaneously or the number of the mussel was obscured then the video was consulted at a later date to substantiate the entrainment and dynamics of individual mussel movement. For each different bed substrate, differences in burial depth, orientation and cluster size were investigated, Table 5.2.

Table 5.2: Different Flume Runs Completed for each Bed Substrate

Cluster Size	Percentage of Shell Buried	Alignment to Flow
	40%	Parallel
		Parallel
1	60%	45 Degrees
		Perpendicular
	80%	Parallel
3	60%	Parallel
5	60%	Parallel

5.2.5 Statistical analysis

Kruskal-Wallis and Mann-Whitney U tests with significance at the 95% confidence interval were performed to assess the importance of difference in bed substrate, burial depth, alignment, cluster size, simulated foot presence, and shell curvature for entrainment velocities. Stepwise logistic regression (Hosmer and Lemeshow, 2000) was used to assess the significance of the different variables (substrate, burial depth, alignment, shell curvature, simulated foot presence, mussel length and mussel weight) on the entrainment velocity of freshwater pearl mussels. This analysis was undertaken using a generalised linear model (GLM) with a log-link and Quasi-Poisson error distribution to account for underlying heteroscedasticity of the data (Zuur et al., 2009) and correct for over-dispersion within the model. As logistic models assume there is no correlation between explanatory variables, co-linearity between explanatory variables was checked by producing scatter plots between each pair of variables. Scatter plots revealed mussel weight was highly correlated with mussel length so was removed from model analysis. Model selection was completed using step-wise reduction (Hosmer and Lemeshow, 2000) whereby the model was run with all non-correlated explanatory variables, and then the least significant variable removed. This was repeated until all variables remaining were significant. In this study, a variable was deemed insignificant if it had a p value greater 0.05 and was therefore excluded from the model. An ANOVA was undertaken to select the model with the highest predictive power. All statistical analysis was undertaken using R Studio version 0.97 (R Development Core Team, 2012) and the ime4 package (Bates et al., 2012).

5.3 RESULTS

Field observations showed that mussels across all habitats tended to have around 55 to 65% of their shell buried and were aligned parallel to the flow or at a slight acute angle to the flow with median values ranging from 18º to 60º. Foot presence was notability higher in the sandy substrate (60-65%) compared to the coarser bed substrates of gravels, cobbles and boulder (0-25%). The results of the field surveys are summarised in Table 5.3.

Table 5.3: Summary of Field Observations

Substrate Type	D50 (mm)	Average Water Depth (m)	Water Temperature (˚C)	Median Orientation to Flow (°)	Average Length (mm)	Average Percentage Burial Depth	Percentage of Mussels with Foot Visible (Y/N)
Sand/Gravels	21	1.05	5.7	18	97.56	68.69	60
Gravel/Pebbles	45	0.37	6.5	35	92.85	54.59	11
Gravels/Pebbles/Cobbles	64	0.81	5.4	60	97.62	56.49	0
Gravels/Pebbles/Cobbles	70	0.36	6.7	18	77.63	57.86	20
Boulder/Cobbles	105	0.38	5.7	22	109.02	64.70	26

5.3.1 Entrainment velocities

The velocity required to entrain a single mussel placed on a plane bed was between 0.5 and 0.8 m s^{-1} with an average value of 0.6 m s^{-1} (Table 5.4). In sand, gravel, mixed gravel/cobble bed and cobble/boulder bed substrates near-bed velocities for entrainment where on average 0.86 ms^{-1}, 0.95 ms^{-1}, 1.01 ms^{-1} and 1.42 ms^{-1} respectively (Table 5.4). On the mixed gravel/cobble and cobble/boulder bed runs 20% and 80% of mussels respectively were not mobilised. Average entrainment velocity across all habitats, burial depths, orientations and cluster sizes was 1.04 m s^{-1} (Table 5.4).

Table 5.4: Summary of Entrainment Results for each Substrate for 60% Burial Depth & Alignment Parallel to Flow

Substrate	Range of Entrainment Velocities (m/s-1)	Average Entrainment Velocity (m/s^{-1})	Percentage of Mussels which Resisted Entrainment
Sand	0.7 to 1.1	0.86	0
Gravel	0.8 to 1.1	0.95	0
Mixed Sand/Gravel/Cobble	0.9 to > 1.5	1.01	6
Boulder/Cobble	1.2 to > 1.5	> 1.5	94

5.3.2 Parameters effecting Entrainment

The results of the individual runs investigating the different parameters thought to be significant in affecting mussel entrainment velocity are detailed below.

5.3.2.1 Substrate type

A Kruskal-Wallis test revealed statistically significant different substrate types [H=247.37, 4 d.f, **P=**<0.001]. Post-hoc testing too showed that there was no significant difference between gravel and mixed-bed substrates, but there were differences between all other substrate types (Figure 5.4a). In general, it was found that the coarser the bed substrate the higher the velocity required to entrain mussels. Most of the mussels in the cobble-boulder dominated habitat failed to be entrained at velocities more than 2 m s^{-1}.

5.3.2.2 Burial Depth

A Kruskal-Wallis test revealed that there was a statistically significant difference (P < 0.05) of using burial as protection mechanism to resist entrainment [H=43.05, 3 d.f., **P=** <0.001]. Post-hoc testing however showed that there was no significant difference between a burial depth of 40%, 60% or 80%, but being buried into the substrates did provide greater resistance to entrainment than not being buried at all (Figure 5.4b). An unburied mussel had an average entrainment velocity of 0.62 m s^{-1} compared to a buried mussel with an average entrainment velocity of 1.02 m s^{-1}.

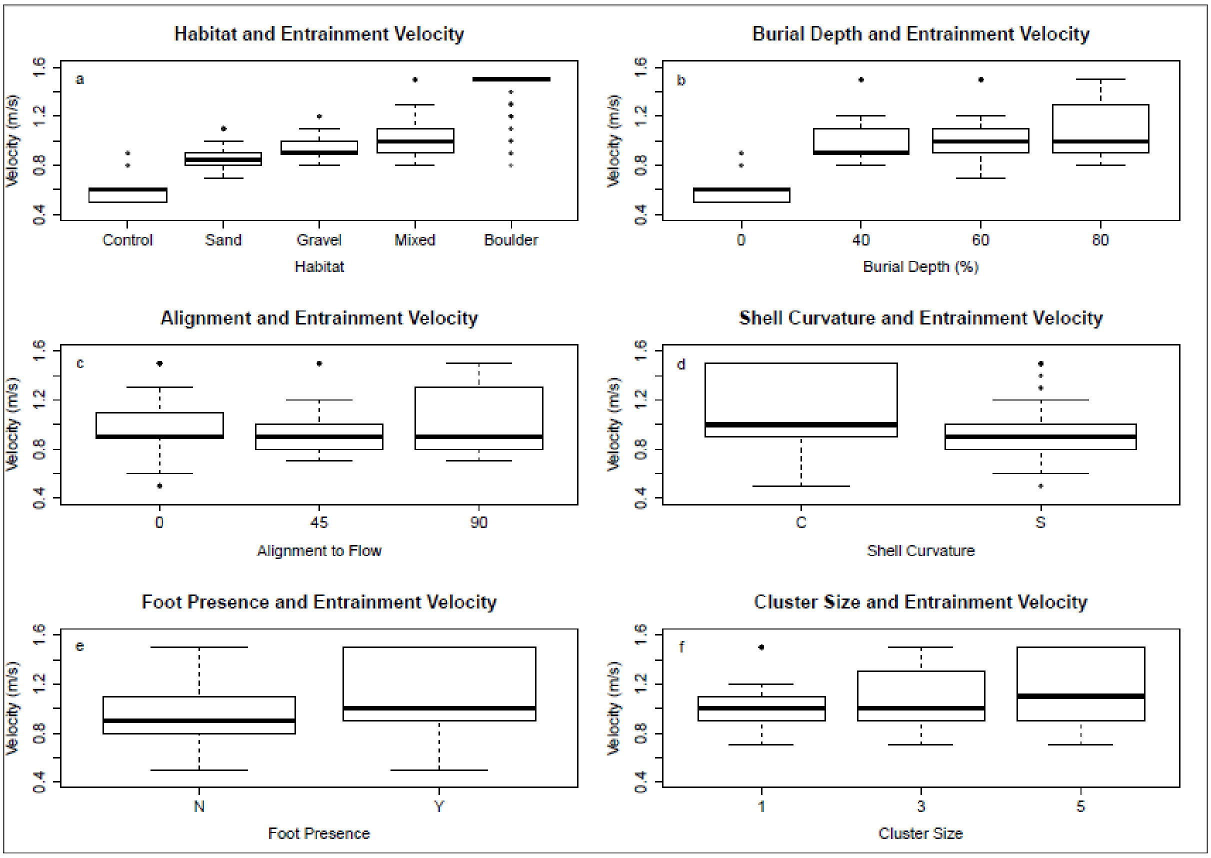


Figure 5.4: An analysis of mussel entrainment velocities relating to (a) substrate type, (b) percentage mussel burial, (c) mussel alignment to flow, (d) shell curvature - s is straight and c curved, (e) foot presence - n is No and Y is Yes and (f) cluster size

5.3.2.3 Alignment

A Kruskal-Wallis test revealed that there was no statistically significant difference ($P < 0.05$) between mussels which were aligned parallel to the flow as mechanism to reduce drag and resist entrainment, to those sitting at an acute angle (45˚) or perpendicular to the flow [H=1.689, 4 d.f., **P**=0.4298] (Figure 5.4c). Average entrainment velocities for mussels positioned parallel, acutely and perpendicular to the flow were 1.06 m s^{-1}, 1.00 m s^{-1} and 1.03 m s^{-1} respectively.

5.3.2.4 Shell Curvature

A Mann-Whitney test revealed that mussels which had a curved shell (Figure 5.5) were statistically better at resisting entrainment at the 95% confidence level [W=28719, **P**= <0.001] than those with a straight shell (Figure 5.4d). A curved shell was found to increase average entrainment velocity by 0.12 m s^{-1}. A straight shell had an entrainment velocity of 0.97 m s^{-1} compared to a curved shell which had an entrainment velocity of 1.09 m s^{-1}.

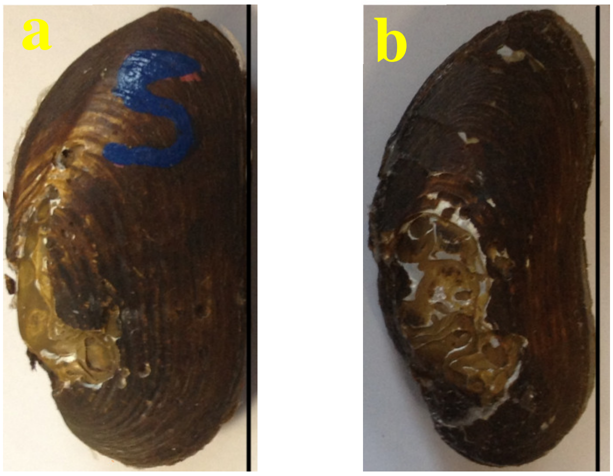


Figure 5.5: Difference between a) straight and b) curved shell morphology

5.3.2.5 Simulated Foot: Absence/Presence

A Mann-Whitney test revealed that mussels which had a simulated foot were statistically better at resisting entrainment at the 95% confidence level [W=17343, **P**= <0.001] than those without (Figure 5.4e). Foot presence was found to increase average entrainment velocity by 0.10 m s^{-1} from 0.98 m s^{-1} to 1.08 m s^{-1}.

5.3.2.6 Cluster size

A Kruskal-Wallis test revealed that increasing cluster size had no significant effect ($P < 0.05$) on mussel entrainment velocity [$H=1.77$, 2 d.f., **P**$=0.4131$] (Figure 3f). Average entrainment velocities for mussels grouped in clusters of one, three or five were 1.05 ms^{-1} 1.10 $m\ s^{-1}$ and 1.13 $m\ s^{-1}$ respectively.

5.3.2.7 Statistical Modelling

Stepwise logistic regression showed that substrate, foot presence, mussel burial depth, mussel length, and shell curvature were sufficient to explain mussel entrainment velocity. Substrate, burial and mussel length were all positively correlated suggesting that the greater the substrate size, burial depth and mussel length then the greater the velocity required for a mussel to be entrained. Simulated foot presence and shell curvature were both dichotomous variables i.e. foot presence is either 'yes' or 'no' and shell curvature is either 'curved' or 'straight' a positive or negative correlation highlighted whether one particular state increased or decreased entrainment velocity. The presence of a simulated foot was found to increase entrainment velocity, where as having a straight shell was predicted to decrease entrainment velocity. Substrate was predicted to be the most significant explanatory variable with a p value of < 2e-16 suggesting substrate has a critical role in the entrainment velocity of freshwater pearl mussels.

5.4 DISCUSSION

5.4.1 Physical Habitat

This study provides the first direct measurements of water velocities at which freshwater pearl mussels are entrained and their effectiveness in utilising their habitat through burial, alignment and sheltering in order to protect themselves from entrainment. An indoor recirculating flume was used to undertake controlled replicated experimental manipulations. The experiments were designed to quantify the different velocities required for mussel entrainment. Also it allowed the effectiveness of burial, alignment and sheltering in order to resist entrainment to be measured within a controlled environment. Previous studies have used a similar approach to investigate the effect of current velocity on feeding (Widdows et al., 2002), burrowing behaviour (Allen and Vaughn, 2009) and the burial and orientation of freshwater mussels (Perles et al., 2003), thus it is assumed that this a viable method to investigate mussel entrainment velocities. Large boulders which provide good bed stability have been found by numerous studies (Vannote and Minshall, 1982; Young and Williams, 1983; di Maio and Corkum, 1995; Gangloff and Feminella, 2007; Hastie et al., 2000; 2001; 2003) to be an important habitat element for mussels as they provide protection from the scouring flows of flood events. Hastie et al.'s 2001 study investigating freshwater pearl mussel populations within different habitats pre- and post- 100 year flood on the River Kerry, Scotland, highlights this well. Mussels occupying boulder-dominated sections of channel have been found to experience lower scour, displacement and mortality than those in pebble dominant substrate which suffered a population reduction of up to 40% (Hastie et al., 2001). In the current study only 4% of mussels in the experiments with mixed boulder-cobble substrates were entrained at velocity of 1.4 m s^{-1}, whereas in the mixed cobble, pebble and gravel experiments, many mussels (94%) were entrained at velocities of 1.0 m s^{-1}. Observations and video recordings of the flume experiments provide some explanation as to the importance of the bed stability provided by the largest boulder and thus the improved ability of mussels to avoid entrainment. It was observed that the scouring of bed particles surrounding individual mussels played an integral role in determining the entrainment velocities in the sand-bed runs. In the sand substrates once the substrate started to become scoured away the mussel would become unstable and sway until it became completely free from the substrate. The mussel would then "shuffle", "twirl" and "winnow" around the bed until the velocity was high enough to pick the mussel up and entrain it downstream. The presence of larger cobbles and boulders meant that once the sand and finer gravels around the mussel had been scoured away the mussels would often avoid entrainment by subsequently becoming trapped within the boulders or protected in the lee of boulders.

Mussels have the ability to affect bed stability, sediment transport and their resistance to entrainment through their morphology (size and shape), flow alignment, burrowing activity and by living in clusters (Allen and Vaughn, 2011). Mussels can influence bed stability in two ways: (1) destabilise the bed by actively burrowing into the sediment, (2) increase bed stability by living deeply buried within the bed substrate (Allen and Vaughn, 2009). Field observations showed that freshwater pearl mussels are commonly found in tight clusters across a river reach, although in some rivers they can create almost a blanket over the bed, which is commonly known as a 'mussel bed' (Strayer 2008). The ability of freshwater mussels, of varying species, to cluster and live in 'mussel beds' has been shown to increase bed stability and cohesion (Zimmerman and de Szalay, 2007) and in tidal mussels be important for growth and survival (Koppel et al., 2008). It has been suggested (Widdows et al., 2002; Zimmerman and de Szalay, 2007) that the ability of freshwater mussels to cluster can in fact increases bed stability by increasing sediment, shear stress and cohesion. However, Zimmerman and de Szalay (2007) found that despite dense clustering increasing bed stability did not reduce sediment erosion. The ability of freshwater mussels to increase bed stability has been shown to increase the resistance of stream beds to scouring during high flows and aid resistance of mussels to entrainment (Johnson & Brown 2000; Hardison & Layzer 2001; Zimmerman and de Szalay, 2007). In this study, this was not found to be the case. Increased cluster size failed to have a statistically significant impact on entrainment velocity. Potentially, this was because the replica mussels, in this study, lacked a muscular foot to help to bind the surrounding substrate or because individual mussels within a cluster were encased within a thinner boundary of sediment which will be more easily eroded than mussels which sit individually on the bed. In addition, when Moorkens and Killeen (2014) analysed near-bed velocities for pearl mussels under low flow they found that mussels living is bigger clusters were located in areas with a higher average velocity. However the mussel densities ranged from less than 10 m^{-2} to over 50m^{-2} with average velocities of 0.18 m s^{-1} and 0.30 m s^{-1} respectively suggesting that the cluster sizes used in this study were not big enough to demonstrate the benefit of clustering.

Shell morphology can also effect substrate erosion (Watters, 1994). Mussels with smooth shells exposed increase near-bed turbulence and thus destabilise the surrounding bed whereas mussels with textured shells reduce the turbulence caused by the shell being exposed and thus reduced erosion (Vogel, 1994 and Watters, 1994). When applied to entrainment velocity, mussels with a more textured shell would be expected to be entrained at higher entrainment velocities than those with a less textured shell. Mussels with a more curved shell had on average an entrainment velocity which was 0.12 m s^{-1} higher than those with a straight shell. Although shell curvature was considered here and not shell texture as it easier to depict the difference between a straight and curved shell rather, studies have suggested that just a more sculptured shell will increase entrainment velocity (Stanley, 1981; Watters, 1994; Bartsch et al., 2009; Hornbuagh et al., 2010). Therefore using shell curvature is still a valid variable for investigating the effect of shell morphology on entrainment velocity. The fact that foot presence was found to be significant in increasing entrainment velocity poses interesting questions as to how useful this device is with live mussels in anchoring the mussel to the bed. Interestingly mussel length was found to be positively correlated with entrainment velocity so the greater the length of the mussel the higher the entrainment velocity. Based on previous work the opposite would be expected, as the longer the mussel the greater the amounts of shell exposed, and thus the greater the amount of shell exposure. The same can be said for increasing burial depth. It would be expected that, as burial depth increased, near-bed turbulence would decrease and therefore the entrainment velocity would increase. Studies by Thom and Berg (1985) and Di Maio and Corkum (1997) have supported this and highlight the importance of the ability of freshwater pearl mussels to burrow into the bed substrate to avoid exposure to strong scouring forces, dislodgement and entrainment by high flows. However, increasing burial depth (40%, 60% and 80%) was not found to increase entrainment velocity significantly. Yet mussels which were totally exposed, compared to mussels partially buried, did increase average entrainment velocity from 0.62 m s^{-1} to 1.02 m s^{-1} respectively. To reduce scour and drag mussels can align or orient themselves parallel to the oncoming flow. The effectiveness of a mussel's ability to reduce scour, drag and shear stress to avoid dislodgement and entrainment by being parallel to the flow did not significantly increased entrainment velocity. Increasing the burial depth of a mussel's shell and changing mussel alignment (parallel, acute, perpendicular) potentially did not affect entrainment velocity because once the mussel had been dislodged from the river bed it did not require a greater velocity to entrain the mussel. Also in bed substrates dominated by cobbles and boulders the protection provided by sheltering behind the boulders potentially outweighs the relatively small increase in burial depth or change in alignment. It may therefore be more useful to consider the importance of burial depth in terms of ability to avoid dislodgement and becoming exposed to the flow rather than looking purely at the entrainment velocity

5.4.2 Implications for Conservation and restoration

This study further highlights the need to ensure river management practices do not disturb or destabilise the boulder dominated reaches in which freshwater pearl mussels reside. When current predictions for future climate are considered this becomes even more important. The predicted increase in the magnitude and frequency of high flow events (Werritty, 2002; Prudhomme et al., 2003; Cameron, 2000; 2006) would mean that mussels living in the less stable sand and gravel-bed dominated reaches would be disturbed on a more regular basis. In addition, there may potentially not be a long enough gap between flood events for the population to recover through reproduction. Mussel populations inhabiting the more stable reaches which can within stand higher flows potentially act as a strong-hold for the species survival and thus should be protected. This should also be considered when reintroducing captive breed mussels into the wild. Reintroduced mussels which are placed in the more stable boulder dominated reaches would be better protected from increasing bed scour and entrainment and thus potentially have a better chance of survival in the short-term and with changing climate.

5.5 CONCLUSION

Based on the results in this study it is suggested that physical habitat is the most important parameter in allowing freshwater pearl mussels to avoid entrainment. A physical habitat which contains large boulders was found to be the best habitat for allowing mussels to avoid entrainment, as the boulders allowed the mussels to shelter and avoid being moved by the fast flowing water. Foot presence, burial depth, mussel size and shell curvature were also found to be important parameters in allowing mussels to avoid entrainment. The results from this study further highlight how important physical habitat will be for mussels to withstand the higher frequency of high magnitude flows predicted with future climate change. The ability for mussels living in these sites to avoid entrainment means that these sites are important populations to monitor. This is because they are important sites for recruitment, and to ensure population recovery after significant population losses due to high flow events. Thus protecting these sites is important to ensure the survival of the freshwater pearl mussel in the future.

5.6 SUMMARY

- The effect of the different parameters (bed substrate, mussel burial depth, mussel curvature, mussel alignment, shell curvature and the presence of a simulated foot) on entrainment velocity was tested in a recirculating flume.
- Bed substrate was found to have the biggest influence on mussel entrainment velocities with averages of 0.86 ms^{-1}, 0.95 ms^{-1}, 1.01 ms^{-1} and 1.42 $ms^{-1}$for sand, gravel, mixed bed and boulder beds respectively.
- Stepwise logistic regression showed that bed substrate, foot presence, mussel length, mussel burial depth and shell curvature were sufficient to explain mussel entrainment velocity.

CHAPTER 6

A Catchment-Scale Model to investigate which Freshwater Pearl Mussel Habitats are most Vulnerable to Climate Change

6.1 INTRODUCTION

A river's hydrological regime is a key control of the ecological health of a river system, as it affects the flow, channel geomorphology, water quality and habitat availability (Gilvear et al., 2002). Understanding and improving the ecological health of river systems in the UK has become increasingly important as river managers strive to ensure that a greater number of rivers achieve a 'good ecological status' in accordance with the EU Water Framework Directive and other European legislation. In the UK, currently only around 38% of water bodies are reaching good or high ecological status, with a target to improve this to 60% by 2021 (Priestley, 2015). In Scotland this value is higher, with 65% of water bodies reaching good or high ecological status, with the aim to increase this to 97% by 2027. The ecological health of a river is often undermined by the societal need to manage river flows and other river habitat attributes and their surrounding catchment for water supply, hydroelectric power, recreation, forestry and agriculture. All of these activities have a knock-on effect on the flow regime and flow hydraulics of the river, either directly or indirectly. This in turn affects aquatic biodiversity and the ecological health of rivers by altering physical habitat, longitudinal and lateral channel connectivity and life history patterns (Bunn and Arthington, 2002). In Scotland, river regulation such as dams in the River Tay, River Spey and River Beauly catchments, and land use change such as the drainage of heather moorland and grasslands for forestry, and expansion of arable land (Johnson and Thompson, 2002), are probably the two greatest human induced activities which affect the health of river ecosystems. Both of these activities affect the delivery of water, sediment and nutrients and as a result strongly influence the ecological processes and the make-up of the biological community of a river reach (Poff et al., 2006). Impoundment disrupts the natural hydrological and sediment regime of the river, trapping water and sediment behind the dam leading to geomorphic adjustments by the river downstream and upstream through incision, aggradation, channel widening or narrowing, change in channel pattern (wandering, braided, meandering) or through loss of riparian vegetation (Petts, 1979, 1980; Ligon et al., 1995). This can lead to the loss of, or reduction in, the physical habitat required by certain species to survive or complete their life cycle, or the removal of the flow variability required to trigger migration or reproduction (Bunn and Arthington, 2002; Gilvear et al., 2002; Moir et al., 2004). In addition, dams disturb the river continuum and are a barrier to fish migration, impeding their ability to reach spawning habitats in upstream tributaries. Changes in land-use have similar effects on river hydrology, geomorphology and ecology by altering the run-off and sediment supply from the surrounding catchment, and the water chemistry. Afforestation, in Scotland for example, has been found to increase stream acidity and reduce run-off leading to reduced stream flows and reduced habitat suitability and fish stocks (Johnson and Whitehead, 1993; Soulsby et al., 2002) Furthermore, during periods of heavy rain improved drainage will increase run-off rate resulting in a reduction in stream base flow levels during drier periods. This can have significant consequences for benthic species such as freshwater mussels, which unlike fish have limited ability to move when habitat availability is reduced. Increases in agricultural and land drainage can also lead to increased levels of silt entering rivers which can clog up gravels and increase fish egg mortality (Hendry et al., 2003). In order to limit the effects of impoundment and changes in land management on rivers and their ecology, a number of management strategies have been put in place. In rivers where dams are present, environmental flow regimes have been implemented whereby water is released with the aim of mimicking the natural flow regime of a river as much as possible (Acreman and Dunbar, 2004); these ensure flushing flows to remove accumulations of fine sediment, spawning or migration flows, and flows to ensure habitat maintenance. Many dams now have a fish ladder situated to one side to ensure that the natural longitudinal connectivity of the river is maintained, so fish can still reach spawning grounds in upland tributaries. Buffer strips are now in place around the banks of the rivers which are used in agriculture to help reduce the input of fine sediment and nutrients into the river.

Climate change now poses a new challenge for river managers because there is expected to be an increase in the magnitude and frequency of flooding in the future (Arnell and Reynard, 1996; Cameron, 2006; Pattison and Lane, 2011; Wilby et al., 2008). This change in the flow regime of the river has the potential to have a marked effect on the hydraulic habitat and physical habitat of rivers, as a change in the flow regime may potentially alter channel cross-sectional geometry, planform, sediment transfer, bed material size and bank stability (Gilvear et al., 2002). In Scotland, where many rivers are important for the conservation of species such as the fresh water pearl mussel (*Margaritifera margaritifera*), Atlantic salmon (*Salmo salar*) and water vole (*Arvicola terrestris*), it is important to try and predict the changing spatial distribution and quality of physical habitat for such species. Here we look at how climate change could potentially affect the physical habitat of the freshwater pearl mussel, a filter-feeding bivalve which lives buried, partially buried or on top of many Scottish river beds. The freshwater pearl mussel is a protected species under the European Habitats and Species Directive, and is listed in Annexes II and V. Additionally, it is listed as ‘endangered’ on the IUCN 1996 Red Data List (Langan et al., 2007). Freshwater water pearl mussels require a clean habitat and an environment free from silt and organic pollutants, often making them a good indicator of habitat health and environmental change due to their sensitivity to sedimentation and eutrophication. Their filtering ability also results in a cleansing of the river bed, providing species such as Atlantic salmon with clean spawning gravels. Numerous studies have investigated the freshwater pearl mussel's ecology (Bauer et al., 1991; Skinner et al., 2003; Hastie, 2006;), physical habitat requirements (Hastie et al., 2000, 2003; Geist and Auerswald, 2007; Henrikson and Alexanderson, 2010) and conservation management (Young and Williams, 1983; Bauer, 1988; Cosgrove et al., 2000; Cosgrove and Hastie, 2001); but less work has been done on the potential threat of climate change. One study, which has considered the potential effect of climate change on the freshwater pearl mussel (Hastie et al., 2003) suggests mixed fortunes for them. Increases in temperature have been found to correlate with improved juvenile mussel growth and recruitment, suggesting that a slight elevation in water temperature may be beneficial in certain locations. This is because glochidia (mussel larvae) grow quicker in warmer temperatures, increasing their survival rate (Hastie et al., 2003). The freshwater pearl mussel, however, relies on Atlantic salmon (*Salmo salar*) and Brown trout (*Salmo trutta*) to complete its life cycle. When the female releases its glochidia (eggs) into the water (thought to be when a threshold temperature is reached) these attach onto the gills of the fish, where they remain until the following spring and are big enough to grow and develop in the sandy substrate of the river bed. If a rise in water temperature results in the glochidia being released early, and out of sync with salmon and trout migration, the mussel recruitment numbers will drop as a result of this climate change (Skinner et al., 2003). Again, small increases in precipitation could benefit the freshwater pearl mussels as it has been shown that mussel recruitment is greater during years of higher rainfall, possibly because the higher flows 'cleanse' the river bed by removing fine sediments and increasing habitat availability (Hastie e al., 2003). Smaller, more frequent floods may be beneficial too as they too help to remove the fine sediment and organic matter that may accumulate in the channel (Hastie et al., 2003; Negishi et al., 2012). Despite the positive benefits of higher flows, the predicted increased in the occurance of extreme floods could lead to reductions in mussel populations, as was shown after a possible 1:100 year flood on the River Kerry in north west Scotland which killed over 50,000 mussels (Hastie et al., 2001) due to the scouring of the river bed. Hastie et al. (2001) also highlighted the importance of habitat stability in protecting mussels from flood flows: it was found that mussel mortality was less in river beds which were composed of larger cobbles and boulders, a result further highlighted by the findings in Chapter 5 of this thesis. Despite the catastrophic effects of exterme floods being understood, at the time of writing no published studies have tried to predict how vulnerable known freshwater pearl mussel populations are to changes in flood flows, and at what flood frequency the physical habitat of the mussel locations becomes unstable and how this varies across a catchment. The advantages of having the ability to do this are twofold: first it allows a more targeted approach to protecting mussel populations from the effects of extreme flooding, because mussel populations which are most vulnerable to the threat of climate change have been identified; and second it aids conservation efforts by ensuring river restoration projects, and attempts to rejuvenate populations by artificially infecting fish with glochidia, are carried out in suitable locations. This study aims to do this by estimating at what flood frequency the river bed of known mussel populations become unstable on the River Dee, Aberdeenshire, Scotland; and by assessing the usefulness of the SEPA Digital River Network (DRN) for investigating the effect of climatically-induced flow changes on the freshwater pearl mussel across the river network. This was achieved by using the DRN model outlined in chapter 4, with the locations and sizes of mussel populations in the River Dee incorporated. The DRN contains spatially modelled channel data such as channel width, slope, depth, sinuosity, confinement and discharge to assign a channel typology, stream power and bedload particle size to each river in Scotland, at 50 metre reach length intervals.

It is hoped that the ability to model the effect of flow changes on freshwater pearl mussels at the river network scale, for the River Dee and other rivers, will also help conservation efforts for freshwater pearl mussels by ensuring that mussels most vulnerable to an increase in flood frequency are identified. It may also open the door to mussels being relocated and placed in river reaches where their physical habitat will not be regularly degraded by the more frequent flood flows.

6.2 METHODS

The River Dee in Aberdeenshire, Scotland was selected as a case study as it has been extensively surveyed for freshwater pearl mussels (*Margaritifera margaritifera*). The River Dee is 1 of 21 rivers across Scotland which has been designated as a Special Area of Conservation (SACs) for freshwater pearl mussels as part of NATURA 2000. The River Dee is 140 km long, and drains an area of 2100 km2 as it flows from the Wells of Dee high up in the Cairngorm Mountains through Deeside to the sea in Aberdeen. Its catchment geology consists mainly of granites and schists, with some limestone outcrops in the lower catchment (Jenkins, 1985). Land use is dominated by heather moorland, forestry, and upland and lowland agriculture, with increasing urban development as you get closer to its mouth in Aberdeen. The annual rainfall varies from 2100 mm in the Cairngorms Mountains to 841 mm in Aberdeen (Cooksley, 2007). At the River Dee's longest recording flow gauge (87 years) at Woodend near Banchory the mean flow is 37.2 m^3s^{-1} and the Q_{MED} flow is 436.8 m^3s^{-1}.

The main stem of the River Dee was surveyed in 2003 as part of a Scottish Natural Heritage (SNH) Site Condition Monitoring (SCM) survey between April and September during low flow conditions. The survey was carried out only along the main stem of the River Dee. SCM is a survey carried out to monitor the condition and conservation progress of designated Special Areas of Conservation in the UK (Cosgrove et al., 2004). The survey, in this case, was done by dividing the bed of each 50m river reach into 1 meter by 1 meter squares and counting the mussels present within each square, using a bathyscope glass bucket. In 20% of the squares searches were carried out for buried and juvenile mussels. For more details of survey methodology refer to SNH's survey guidelines (www.snh.gov.uk/docs/A372955.pdf). A grid reference point for each square was then recorded. These grid references were stored by SNH for future monitoring purposes. The grid reference points for each location where freshwater pearl mussels were found were the taken from SNH and converted to a longitude and latitude value, and imported as a layer into Arc Map's geospatial processing platform.

The ArcMap mussel layer was then overlaid onto the channel stability model for the River Dee, developed in chapter 4 using SEPA's DRN, within Arc Map's geospatial processing platform. The channel stability model developed using SEPA's DRN uses stream power to outline the rate of bedload transport of a D_{84} particle for different flood return intervals (1 in 2, 5, 10, 30, 50 and 100 years). The rate of bedload transport is then used to categorise reaches into 'minor instability', 'unstable' and 'highly unstable'. The size of the D_{84} particle assigned to each reach was based on the allocated channel typology. The DRN's channel typology was developed as part of the WFD49 typology project for SNIFFER (Greig et al., 2006a, b; Matheson et al., 2008), and is based on a modified version of Montgomery and Buffington's (1997) channel classification system for the Pacific North West region of the USA. For Scotland five different channel types were developed and labelled A to F (see Figure 4.4). These were Type A, cascade and bedrock, Type B, plane-bed and step-pool, Type C, wandering, pool-riffle, braided, Type D, active meandering and Type F, passive meandering. A type E channel, which refers to chalk channels are not used in this study as these channel types do not occur in Scotland (Figure 4.4). The D_{84} particle size was selected, as several studies have suggested that movement of this particle size within a reach represents the point that a river channel will become unstable and potentially start to adjust its morphology (Pickup and Warner, 1976; Carling, 1988; Booth, 1990; Olsen et al., 1997). As bed stability has been shown to be one of the key requirements for mussels to survive (Hamilton et al., 1997; Hastie et al., 2000; Negishi et al., 2012) and withstand extreme floods, it assumed that if a mussel population is located within a reach that is predicted to become unstable, then the mussel population in that reach may suffer high mortality rates. The channel stability model also predicts the channel typology, to allow the channel typologies preferred by mussels to be reviewed. More details on the development, assumptions and uncertainties associated with this model can be found in the methods section of chapter 4.

6.3 RESULTS

Along the main stem of the River Dee, 267 river reaches were identified as having at least one freshwater pearl mussel. Of those 267 river reaches only 18 contained more than 50 mussels, and of those 18 river reaches only 4 contained more than 100 mussels. The results here will focus primarily on the 18 locations where more than 50 mussels were counted when surveyed. This is because, despite there being no scientific agreement on what constitutes a viable mussel population (Skinner et al., 2003), it has been suggested that a viable freshwater pearl mussel population will have over 500 individuals, with 20% of those 500 being juveniles (Henrikson and Alexanderson, 2011). Based on this criterion the decision was taken that river reaches which had a population of less than 50 mussels would not be investigated. This is because a mussel population of less than 500 mussels is considered to be dying out, so a population of less than 50 was thought to be unlikely to contain the age structure required to be a viable population and contain many recruiting mussels. Also, isolated mussels may be those in an inadequate or sub-optimal habitat left stranded after being dislodged by flood flows.

The river typology assigned to the river reaches in which the 18 mussel populations where located was reviewed to assess whether there was any clear preference by the freshwater pearl mussels towards one typology. When the river typology preferred by mussels was investigated it was found that out of the 18 river reaches where over 50 mussels were found 13 populations lived in reaches which had been classified as a Type C typology (wandering/braided/plane riffle), two in river reaches classified as Type B (step-pool/plane-bed), two in river reaches classified as Type F (passive meandering) and one in a river reach classified as a Type A (bedrock/cascade) typology (Table 6.1). The preference of freshwater pearl mussels for river reaches with a Type C typology is unsurprising as these reaches would characteristically be associated with riffle areas with a bed substrate composed of a mixture of small boulders, cobbles and sand, which have been suggested in the literature as being good habitat for freshwater pearl mussels (Skinner et al., 2003). When the number of each river reaches assigned to each river typology was reviewed it was found that there was 1637, 4054, 6374, 219 and 526 Type A, B, C, D and F reaches respectively within the River Dee catchment. When reviewing the preferred river typology of freshwater pearl mussels, it was found that although the mussels tended to be residing in Type C typologies, these sections of channel were often found to be downstream from more stable Type F channel typologies. Type F channels have extremely low rates of bedload transport even under 1:100 year flood flows historically and under a climate change scenario. In the three river reaches along the River Dee where over 100 freshwater pearl mussels were counted, it was found the 50 m reach typology, for that 300m section of channel alternated between Type C and Type F. This suggests that there may be some advantage to the freshwater pearl mussels of living in sections of channel like this which enhance their survival or aid in recruitment. Juvenile mussels may prefer the sandier slower flowing river reaches while they are developing, for example. It was also observed that the freshwater pearl mussel populations on the River Dee tended to reside in sections of the river which were classed as having low sinuosity, and preferred sites upstream of tributaries rather than below tributary junctions.

Table 6.1 Flood Return Interval at which Mussel Populations become Unstable

Mussel Site Number	Mussel Population Size	Channel Typology	Channel Instability - Historic	Channel Instability - Climate Change
1	57	Type C	> 1:100 year flood	> 1:100 year flood
2	93	Type F	> 1:100 year flood	> 1:100 year flood
3	115	Type F	> 1:100 year flood	> 1:100 year flood
4	750	Type C	> 1:100 year flood	> 1:100 year flood
5	85	Type C	> 1:100 year flood	> 1:100 year flood
6	55	Type B	> 1:100 year flood	> 1:100 year flood
7	95	Type C	> 1:100 year flood	> 1:100 year flood
8	67	Type C	> 1:100 year flood	> 1:100 year flood
9	59	Type C	> 1:100 year flood	> 1:100 year flood
10	59	Type A	> 1:100 year flood	> 1:100 year flood
11	88	Type C	> 1:100 year flood	> 1:100 year flood
12	50	Type C	> 1:100 year flood	> 1:100 year flood
13	95	Type C	1:50 year flood	1:30 year flood
14	135	Type C	> 1:100 year flood	> 1:100 year flood
15	54	Type C	1:30 year flood	1:10 year flood
16	60	Type B	1:50 year flood	1:30 year flood
17	51	Type C	> 1:100 year flood	> 1:100 year flood
18	52	Type C	> 1:100 year flood	> 1:100 year flood

This may be because the flow will be slower flowing with lower velocities upstream of the tributary junctions, compared to downstream of the tributary junctions where flow velocity and turbulence is increased (De Serres et al., 1999) making it more difficult for freshwater mussels to live. The constant inputs of sediment and nutrients will also make downstream of tributaries less desirable for mussels as they prefer habitats free from nutrients and siltation from increased sediment loads (Skinner et al., 2003). Furthermore, it has been suggested that that freshwater pearl mussels often like sections of channel which are tree-lined because these sections can often have more stable banks leading to less bank erosion, and the overhanging canopy provides shade in the summer months to help keep water temperatures down and reduces algae growth (Skinner et al., 2003). Of the 18 river reaches identified here as containing freshwater pearl mussels 12 were tree lined suggesting freshwater pearl mussel populations do have a preference to tree lined banks in the River Dee.

When the differences between freshwater pearl mussels living in stable and unstable river reaches was reviewed it was found that the three reaches which showed signs of channel instability were all located within a 5 km section of channel and located in reaches with higher levels of sinuosity. In addition, it was found that mussels living further downstream tended to be surrounded by more stable river reaches that remain stable even during extreme flood events (Figure 6.1). The main reason for this is thought to be due the lower slope values in the lower catchment resulting in lower flood stream powers, meaning there is less available energy to dislodge the bed sediments. When the change in channel stability between historic flood frequency magnitudes was compared to climate change-induced flood frequency magnitudes, it was found that 3 of 18 (17%) of the river reaches containing freshwater pearl mussels would become unstable more frequently under a climate change scenario. The remaining 15 river reaches were found in sections of channel classed has having only minor instability issues. In these 15 reaches climate change was found not to change the frequency at which they became unstable when compared to historic flood magnitudes. In all 15 reaches the channel bed remained stable even under a 1:100 year flood (Table 6.1). This suggests that freshwater pearl mussel's preferred habitats within the River Dee which provide them with good protection from flood disturbances. In mussel reaches where channel instability occurred it was found that the frequency of habitat disturbance increased under a climate change scenario. In two freshwater pearl mussel reaches it reduced flood disturbance from every

50 years to every 30 years (mussel site 13 and 16) and in one reach from every 30 years to every 10 years (mussel site 15). Furthermore, mussel site 15 was predicted to have high levels of channel instability during a 1:100 year food under a climate change scenario. This suggests that the mussels in the

population are the most vulnerable to habitat disturbance under climate change flood

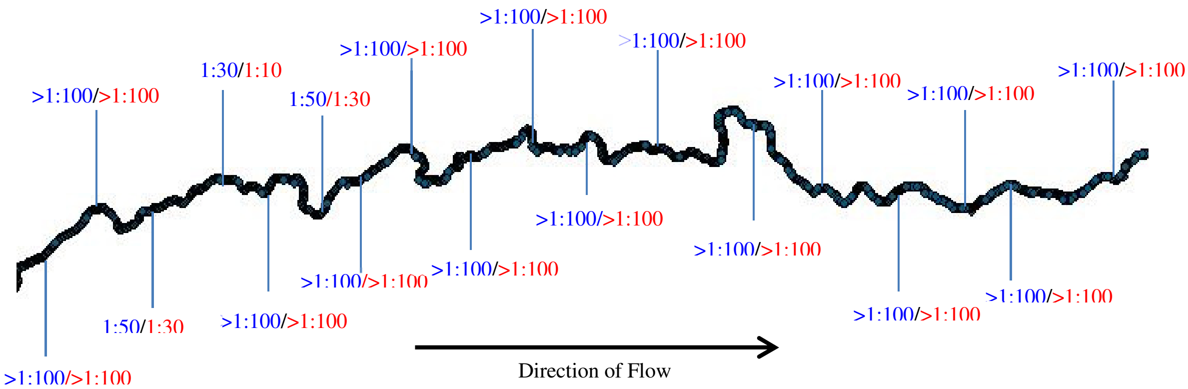


Figure 6.1: Flood frequency return at which the 18 different mussel populations studied here become unstable. The return interval in blue represents the historic flood frequency return interval at which the river bed was predicted to become unstable and the red return interval is the return interval at which the river bed was predicted to become unstable under a climate change scenario.

magnitudes. The increased disturbance and increased channel instability in these reaches in the future due climate change could result in mussels being more frequently crushed, stranded on river banks and dislodged and flushed downstream. As a result, it would be expected that freshwater pearl mussel mortality rates in these reaches will be higher in the future. Figure 6.2 below shows the number of mussel reaches which show minor instability, instability and high levels of instability under historical flood frequency magnitudes, and flood frequency magnitudes under a climate change scenario.

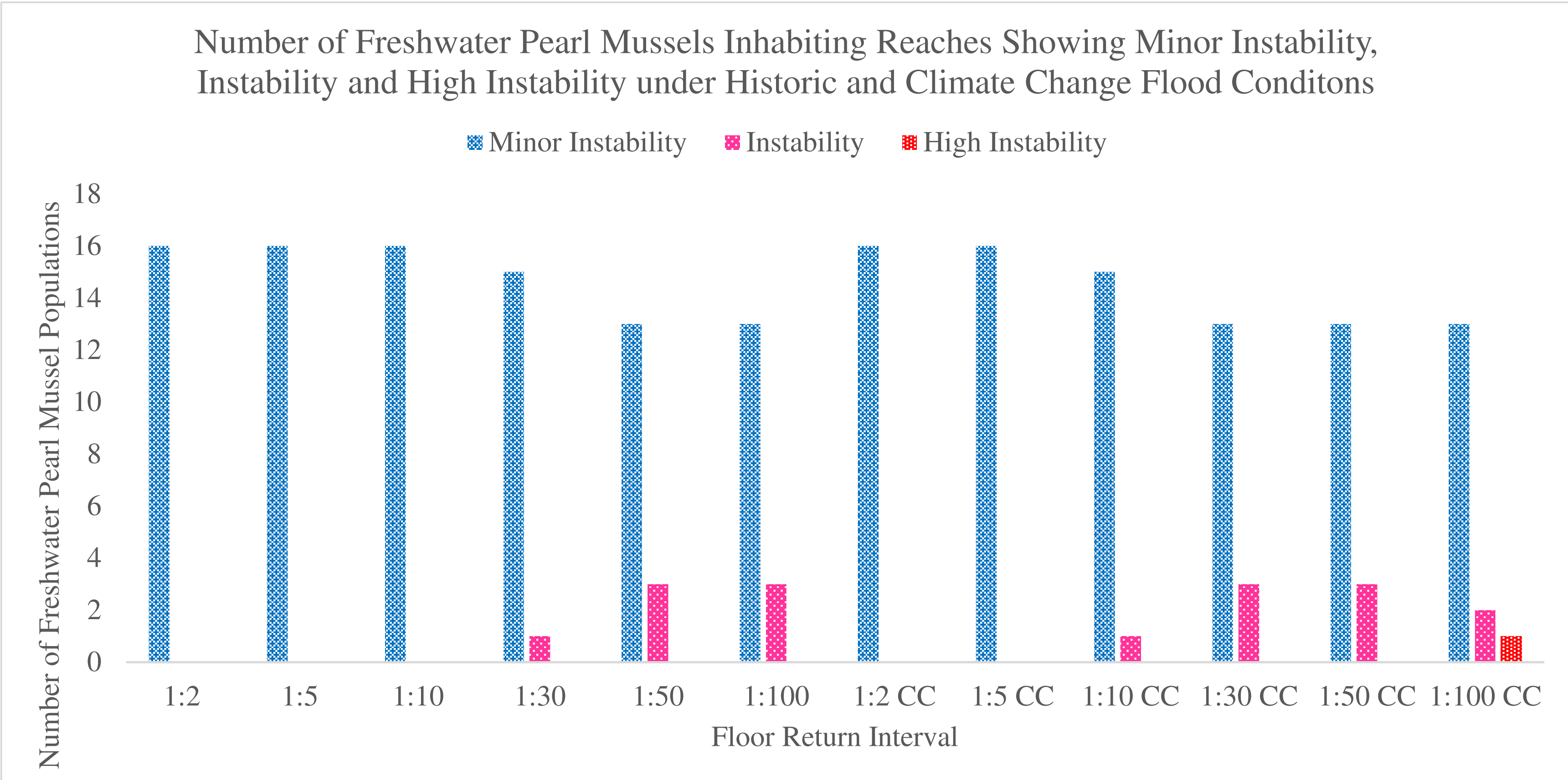


Figure 6.2: Bar chart showing the number of mussel populations mussels inhabiting reaches showing minor instability, instability and high instability at different flood return intervals based on current return intervals and those predicted under a climatic change scenario (denoted as CC on the figure).

6.4 DISCUSSION

The link between ecology, hydrology and geomorphology is widely recognised among river mangers. The recognition of the link between these disciplines, and the requirement for more 'joined-up' thinking has been driven by concerns over the effect of things such as abstraction, impoundment and climate change on riverine ecology; as well as EU legislation in the form of the Water Framework Directive (WFD) (Vaughan et al., 2009). This 'joined-up' thinking could be essential when considering the future of the freshwater pearl mussel. Previous studies have highlighted the importance of bed stability in protecting mussels from extreme flood events (Vannote and Minshall, 1982; Hastie et al., 2001). When the effect of a 1:100 year flood on mussel populations in the River Kerry was reviewed it was found that mortality rates were significantly lower in the reaches with stable boulder-dominated river beds, compared to those with cobbles and gravels which were more easily transported during flood conditions (Hastie et al., 2001). Additionally, less disturbance of the river bed occurred in the boulder-dominated reaches, inferring habitat structure remained more intact, meaning the potential for population recovery after extreme flooding would be greater in these reaches. In the River Dee only 3 out of the 18 freshwater pearl mussel reaches investigated were shown by the DRN model to become unstable at flood magnitudes less than a 1:100 year flood. This suggests that the majority (83%) of the freshwater pearl mussel population studies here inhabit river reaches which remain fairly stable even during high magnitude events such as a 1:100 year flood. Thus looking into the future, it could be suggested that the River Dee in general and these 15 reaches represent key areas to be protected to help ensure the survival of the species in the River Dee.

The majority of the River Dee's mussel populations occupied a Type C channel typology (wandering, braided, plane-riffle), with many reaches likely to be compromised of an armoured bed, and cobbles and gravels. Although, flume studies have suggested armoured river beds coarsen during low flows and are washed out during floods (Parker and Klingeman, 1982), there is competing evidence which suggests that bed surface grain size changes very little, if at all during flood flows (Wilcock, 2001; Wilcock and DeTemple, 2005). A persistent armoured layer has also been reported in field studies using tracer pebbles. Haschenburger and Wilcock (2003) mapped the movement of tracer pebble across half a river bed for a 1:2 year flood and found that the bed was either largely immobile or partially mobile. Meanwhile Church and Hassan (2002) found that 70% of channel bedload with a grain size greater than the median grain size moved during a flood slightly greater than 1:2 years. These studies suggest that the Type C morphologies preferred by freshwater pearl mussels will potentially undergo only minor changes in channel instability. This theory supports the findings of the DRN where for the main channel of the River Dee only 41 reaches and 264 reaches were predicted to show signs of channel instability during a 1:2 year and 1:100 year respectively. Thus, suggesting, Type C river reaches are good locations for freshwater pearl mussels to live and avoid the devastating effects of flood flows. Out of the 13 river reaches studied in this study which the DRN assigned a Type C morphology only 2 showed signs of channel instability at flows below a 1:100 year flood (Table 6.1). In these sites channel instability occurred at a 1:50 and 1:30 year flood under a historic hydrologic regime which reduced to 1:30 and 1:10 year flood under a climatic change hydrological regime. The reason for these reaches potentially becoming unstable at lower flood magnitudes could be due to the channel morphology in these sections having a greater sinuosity and at mussel site 13 the presence of tributary junction less than 300m upstream. The presence of the tributary junction up stream could result in a sudden change in channel forming parameters (discharge and sediment supply) often resulting in dramatic adjustments in channel stability and morphology (Sloan et al., 2001). Meanwhile increased channel sinuosity suggests a greater presence of riffles and potential bank erosion which are often locations avoided by freshwater mussels (Skinner et al., 2003).

It was observed that although the majority of freshwater pearl mussels were found to reside in the Type C river reaches these were often interspersed with Type F (passive meandering) reaches where slope values, stream power values and rates of bedload transport are often extremely low (< 0.001 t m s^{-1}). Due to low stream powers in these reaches, even under a 1:100 year flood conditions Type F river beds are predicted to only undergo only minor channel modifications and have rates of bedload transfer below 0.001 t m s^{-1}. Although, it would be recommended to confirm this with more detailed modelling, if this was found to be the case these reaches may provide a safe haven for mussels during flood events. Thus, theoretically, mussels which were not crushed or washed onto the bank would possibly be washed downstream into these reaches, where they could shelter until the flood passes by, being able burrow into the sediment to avoid being flushed further downstream due to the lower stream power in these reaches. Then theoretical, post-flood, over time may be able move back into more favourable Type C habitat. Although this could be unlikely as freshwater pearl mussels have not been document to move around very much. Conversely, the freshwater pearl mussels may inhabit sections of channel with alternating Type C and Type F typology as they offer refuge to mussels who are dislodged during high flows but keeps the population close enough together to still allow mussel recruitment to occur. However, further research would be recommended to validate this theory. The tendency for mussels to seek refuge in deep, low gradient reaches (like Type F reaches) to avoid scouring flows has been suggested elsewhere in the literature (Howard and Cuffey, 2003; Strayer, 1999; 2013; Gangloff and Feminella, 2007). When Strayer, (1999) looked at south-east New York freshwater mussel assemblages during flood events, it was found that mussels resided in areas of low boundary shear stress, where tracer particle movement was low, allowing the mussels to withstand floods with return intervals of between 3-30 years. Howards and Cuffey (2003) had similar findings when studying freshwater mussel assemblages along the north Californian coast in the USA. Their studies found that mussels tended to avoid riffle and run channel morphologies, and opted for deep pools with low gradients, shear stress and velocity, in which flow conditions therefore remain fairly constant even during more extreme winter flooding.

When the frequency of bed instability was modelled here using the DRN model, it was found that 83% of reaches (15 reaches) occupied by mussel populations remained stable with the potential for only minor channel instability predicted to occur even during a 1: 100 year flood. However, in 17% of reaches (3 reaches) were predicted to become unstable a flood frequency below a 1:100 years. This means on average climate change increased frequency of channel bed disturbance by 20 years in each of these 3 river reaches. In two reaches the frequency flood disturbance increased from 1:50 years to 1:30 years and in one reach it increased from 1:30 years to 1:10 years. In these reaches this would potentially significantly increase the frequency of mussel population loss, and reduce the recovery time to allow population numbers to recover between large flood events. However, it may be beneficial to survey in more detail the location of the mussels within the river bed, and do more detailed modelling of the locations within the bed, to see when they become unstable. Previous work looking at mussel habitat preference (Hastie et al., 2000) has suggested that freshwater mussels showed greatest preference for being around two meters from the bank. Many reasons have been suggested for why this is case, such as drought avoidance, depth, shade provided by riparian vegetation and reduced shear stress (Howard and Cuffey, 2003; Skinner et al., 2003). During flood conditions studies have shown that bedload transport is not consistent across a river reach

(Lenzi et al., 2004; Turowski and Rickenmann, 2009; t al., 2010; Downs et al., 2016). When Downs looked at bedload transport in the River Avon, using impact sensors, he found that bedload transport was highest along the centre line of the channel. In theory, this would mean that mussels living closer to the bank would potentially have a higher chance of withstanding high-flow events than suggested by the model, which assumes bedload transport rate is consistent across the entire reach. A similar assumption was reached by Howard and Cuffey (2003) on Californian coastal streams. They found mussels tended to prefer location closer to the banks, rather than the channel centreline, as they were regions of low stress and low velocity. Thus width-averaged shear stresses may not be entirely appropriate in a modelling context. An improved understanding therefore of where exactly within the channels the mussels are located, and the sediment dynamics within a reach, could be used to better predict how mussels cope with different flood frequencies, and an increased occurrence of high flood events. Consequently, the DRN provides a good screening tool to look at what flood frequency mussel populations become most vulnerable to displacement, and how this will potentially change in the future with climate change. More detailed modelling of the hydraulic and geomorphic processes is really needed to aid conservation decisions. It should also be considered that the slightly more frequent 1:2 year floods events will potentially aid mussel population growth, cleansing the river bed and increasing available habitat (Hastie et al., 2003). However, with juvenile mussels taking 10 years to reach maturity, and many mussel reaches in the River Dee expected to become unstable every 10 years the increase in recruitment may be outweighed by the increase in high flow events, which may reduce the population numbers, if in fact the mussel population in the River Dee are recruiting at all. As the physical and biological interactions are complex, it means making predictions difficult.

The predicted increase in extreme flood events suggested by this study, further adds to the question of what is best management practice to ensure the long term survival of the freshwater pearl mussel. If the frequency of extreme flooding increases, the recovery time available for mussel populations to re-establish themselves will be reduced. When mussel recruitment in Scottish rivers was reviewed in 2010 (Hastie et al., 2010), to assess the long term stability of freshwater pearl mussels, gaps where often found in age-structure of the mussel populations. For example, in the River Dee bank reinforcement work reduced recruitment to the point at which a modal shift in the population structure occurred (Hastie et al., 2010). In other rivers there were gaps in the population structure; for example, significantly fewer mussels aged between 6 and 9 years were recorded. A possible reason for this could be extreme environmental stress during the time when 6 and 9 year old mussels would have been recruited, such as flooding, engineering works, or a pollution event. An increasing frequency of flood events that cause habitat instability and devastation therefore could reduce recruitment in these years, changing the overall age structure of freshwater pearl mussel communities and thus effecting the long-term survival of the species. When this is reviewed in relation to conservation measures to protect the species, it would be recommended to prioritise investigating the effect of climate change on bed stability on reaches with high recruitment rates, to ensure suitable measures are put in place to try and protect these populations. The ability of the DRN to provide an indication of which populations are most vulnerable to channel instability, and at what flood frequency, in a quick and easy manner, means it could be a useful screening tool in identifying areas for closer investigation when combined with knowledge already available on recruitment patterns of freshwater pearl mussels in Scottish rivers.

The DRN could also prove useful in conservation efforts such as rejuvenating of populations by artificially infecting fish, or possible mussel reintroduction programs by allowing the selection of sites which provide the freshwater pearl mussels with the best chance of survival. The capability of the DRN to give an indication of channel typology, bedload size and channel stability would allow a catchment to be screened for possible locations before going into the field. This would allow field surveying to be carried out with a more targeted approach, and therefore the ability to locate suitable sites more quickly and with less intensive field survey work. Use of the DRN on other rivers known to contain freshwater pearl mussels in Scotland could help identify patterns in habitat preference, and further increase the advantage of using the DRN to aid in the selection of translocation locations. For example, if in other Scottish rivers mussel populations tended to be found in locations which alternate between Type C and Type F reaches, then this same pattern can be looked for in other rivers, or recreated in restored channel reaches, to ensure mussels reside in locations that will provide habitats that will aid their long term survival and stability. The same theory can be used to identify mussel populations located in reaches with a more boulder-dominated substrate, which previous studies have identified as being a key area for population recovery, and thus could be a key to ensuring the survival of the species long-term under climate change conditions (Vannote and Minshall, 1982; Hastie et al., 2001). It may also be suggested that conversation efforts be focused more on rivers which contain very high numbers of freshwater pearl mussels and like the River Dee where the river bed is predicted to remain stable even under high magnitude flood events such as a 1:100 year flood.

The ability to identify mussel populations potentially most at risk from climate change, using the DRN model, further highlights its ability to aid management decisions. Having an indication of which mussel populations reside in locations which are important for population recovery after extreme flood events, and which populations live in vulnerable locations, can ensure funding and reintroduction projects are carried out in suitable locations. However, it is important to also recognise the limitations of the DRN. The DRN for example assumes that bedload transport is consistent across the entire length of the reach, that discharge increases linearly downstream, and that all flood water is contained within the channel and is available for bedload transport, which then makes the river bed unstable. However, in reality during flood conditions, this may not be the case, as water that is not accommodated by the channel will spill over onto the floodplain and thus not be directly available to transfer sediment, and thus the DRN will possibly over-estimate a reaches' ability to transfer sediment. Additionally, as discussed earlier, bedload movement across a reach varies (Downs et al., 2016), meaning there is the potential for bedload to be moving in one section of the channel and not in another. Despite this, with increasing discharge, the more power the river has to erode and modify its geometry, the greater stress on the mussels and surrounding bed, meaning the model will represent the increasing stress on the river bed and thus what the mussels will potentially be subjected to it; and how this changes with climate change. As the model relies on the use of spatial data, the model is only as good as a resolution of the data used. The use of spatial data makes the model quick and easy to develop, but can mean that there can be slight inaccuracies in channel width, depth and slope, which could lead to discrepancies between the model output and what is found in the field. However, it has been found that often the pattern of change along a river is consistent; it is just the values are slightly out, meaning that where there are big drops and increases in stream power the model will show the same increase and decrease, but the value might be slightly different. It is expected that as the resolution of spatial data improves so will the accuracy of the models outputs. For more detail review of the DRN assumptions and uncertainties refer to the methods section in chapter 4 of this thesis. As result, it would be recommended that the DRN is used more as a screening tool to aid in the conservation of freshwater pearl mussels, and not as a replacement for field surveying and more detailed ecological, hydrological and geomorphological modelling.

6.5 CONCLUSION

The ability to be able to predict how future changes in climate may affect benthic aquatic species is an important task currently facing river managers and freshwater ecologists. The DRN offers a possible screening tool to aid efforts aimed at conserving the freshwater pearl mussel, and other benthic organisms. This is because the DRN provides a means of observing the freshwater pearl mussel populations most vulnerable to an increase in the frequency and magnitude of flood flows predicted with climate change in the river network or even possibly on a national river scale. In addition, it also may provide a tool to identify populations which will be important for population recovery post high-flow events and maybe the ability to look for suitable reintroduction sites. It is hoped that the ability to identify freshwater pearl mussel populations most vulnerable to the threat of an increased frequency of high magnitude floods will aid conversation efforts by ensuring funding is directed towards mussel populations which will benefit most and are key to the survival of the species. When the18 mussel populations on the River Dee were reviewed it was predicted that climate change would only increase the frequency at which three freshwater pearl mussel beds would become unstable. In the majority of reaches studied (83%), it was found that even with climate change induced changes to the hydraulic regime they would remain stable even under 1:100 year flood conditions. In the three reaches where a climate change hydrologic regime did increase the frequency of habitat disturbance in freshwater pearl mussel reaches, there was on average a 20 year increase the frequency of habitat disturbing flood flows. This would significantly reduce the time available for population recovery in between flood events in recruiting populations and thus have considerable consequences for the long-terms survival and stability of the species in these reaches. There may be benefits however in reduced levels of siltation. However, the population ecology of freshwater pearl mussels is complex and their long-term fate under present and post climate change conditions is still unclear.

6.6 SUMMARY

- Of the 18 mussel populations investigated here 3 would be negatively affected by climatically induced flow changes, and as a result of changes in bed stability. The remaining 15 sites would see no change in the frequency of bed instability due to climate change.
- In the three mussel reaches which were predicted to become unstable at flow magnitudes less than 1:100 years, climate change was predicted to increase the frequency flood disturbance to the river bed by 20 years.
- The DRN potentially provides a useful screening tool to aid in the conservation of the species by helping: i) to identify mussel populations most vulnerable to change, ii) identifying mussel populations which are key population recovery post flood event, iii) identifying suitable areas for reintroduction, translocation and restoration.

CHAPTER 7

Conclusion: Adding to the Puzzle

7.1 INTRODUCTION

The study of river science and the fluvial system can be viewed as a jigsaw puzzle, which over the years has been partially put together, that will help river managers gain a fuller understanding of the fluvial system and how it operates. This thesis aims to put in place a small piece of this puzzle. Currently, it is well documented how future changes in climate will affect the frequency of, and the magnitude of, floods in a general sense; for example we know to expect to experience high-magnitude events more frequently in northern Britain (Kay and Jones, 2012). However, at present we know less about how rivers in Scotland will respond to this change in their hydrological regime in relation to channel stability, sediment transfer and morphology, and how this may affect river ecology. In addition, fluvial geomorphologists now have growing access to increasing amounts of spatial data, that will allow them to understand better how channels may change following the predicted climate-induced hydrological changes, and where these changes may be most prominent within a river catchment. Here, in the final chapter of this thesis, the aim is to draw on the findings of this research. To show how the findings of this study go some way towards answering the question of how spatial data can be used to predict how the anticipated changes in climate change driven flood regimes could potentially affect channel stability, sediment transfer, channel morphology and aspects of river ecology at the catchment scale. Finally, then look to see how future studies can build on this, to add further small pieces to the river science jigsaw puzzle.

7.2 SUMMARY OF FINDINGS

The predominant aim of this thesis was to investigate how spatial data can be used to look at how flood frequencies and magnitudes in the past, and into the future under a climate change scenario, will potentially effect channel geomorphology, ecology and management at catchment scales, and conceivably at the national scale, using Scotland as a case study. To achieve this primary aim, five objectives were outlined and addressed in Chapters 2 to 6 of this thesis. Below, a synthesis of the findings from each objective are summarised.

7.2.1 Objectives

Objective 1: to examine long-term flow records to look at the frequency of geomorphologically significant high flows on a number of Scottish rivers in the past, and potential future changes.

This objective was addressed in Chapter 2 of this thesis. Here the aim was to investigate whether in Scotland floods which would potentially cause geomorphic change exhibited non-stationary behaviour, as has been suggested for peak flow events by a number of previous studies (Steel, 1999; Lane, 2008; Werritty, 2002; McEwen, 2010). These studies have suggested that flooding has a cyclic nature, whereby it cycles between flood-rich and flood-poor periods. In addition, the potential effect of future climate change on the frequency of geomorphologically active floods was investigated. The main conclusions from this are:

- 'Geomorphologically-rich' and 'geomorphologically-poor' periods were identified in all six rivers, when the number of days between geomorphic flood events was investigated. This pattern is consistent with previous studies which have suggested that flooding exhibits non-stationary behaviour, and flooding in the past has gone through ‘flood-rich’ and ‘flood-poor’ periods. However, when the number of days a geomorphic flood occurred was investigated, only the Earn exhibited this non-stationary behaviour.

- The results from a climate-enhanced record varied between: i) simple enhancement of current trends, ii) a complete removal of the cyclic trend of ‘flood-rich’ and ‘flood-poor’ periods, suggesting the move towards a more stationary regime, with more consistent high-magnitude flood events over time, or iii) the appearance of a more marked ‘flood-rich’, ‘flood-poor’ cycle
- A review of the number of days between bedload movements showed that four rivers potentially have undergone at least one statistically significant shift in bedload dynamics. When the same trends were looked for within a climate-enhanced record only one river exhibited a cyclic trend in the number of days between bed particle movements.

Objective 2:to investigate the use of stream power as a proxy for channel change induced flood scenarios, and whether it can be used as a pre-screening tool by river managers to highlight potential areas of channel instability on a national scale.

This objective was addressed in Chapter 3 of this thesis. Here the aim was to investigate the use of the stream power concept with Scottish rivers, using in the first instance the thresholds suggested by Andrew Brookes in 1987a, b for managed rivers in England and Wales. In addition, the potential for using stream power as a tool to predict areas that may become unstable as a result of climate change was investigated. The main conclusions were:

- Based on the data used in this study it was found that stream power thresholds of less than 10 Watts m^{-2}, greater than 35 Watts m^{-2} and greater than a 100 Watts

m^{-2}, found by Andrew Brooks in 1987b to predict channel change through deposition, erosion and channel shifting for managed rivers in England and Wales, are too low to represent the bedload transport process (depositional or erosional) within upland catchments within Scotland.

- A simple threshold of 465 Watts m^{-2} was suggested to mark the change in reach processes from depositional-dominant (less than 465 Watts m^{-2}) to erosion-dominant (greater than 465 Watts m^{-2}). Using this threshold improved the accuracy of predicting river channel fluvial process types by 10%, when compared to a threshold of 35 Watts m^{-2}.
- Even though stream power provides a quick and easy way to investigate differences in a channel's ability to erode and transport sediment, its ability to predict more in-depth channel processes is limited, as it fails to take account of bank material and bedload particle size. However, using stream power can still be a useful initial screening tool to look for areas where channels have a higher chance of being unstable, and highlighting general patterns in channel process over large spatial scales.

Objective 3: to use and develop the Scottish Environmental Protection Agency's (SEPA) Digital River Network (DRN) to explore changes in channel stability and rate of bedload transfer at different flood frequencies, and with climate change induced flood scenarios.

This objective was addressed in Chapter 4 of this thesis. Here the aim was to investigate the use of spatial data to explore the effect of different flood frequency magnitudes, and predicted changes in climate, on channel stability and the rate of bedload transfer at the catchment scale. The main conclusions from this are:

- SEPA's DRN (Digital River Network) was shown to provide a useful screening tool for looking at changes in channel stability and bedload transport at the catchment scale for different flood frequencies, and investigating the impact of future climate change. It was also found to accurately predict areas of instability during a very high flow event on the River Dee, Aberdeenshire in January 2016 – a timely and fortuitous opportunity for validation under extreme conditions (possibly > 100 year recurrence interval).
- The DRN suggested channel instability (bedload transport) was greatest in the tributaries where channel widths were narrower, and channel slopes greater than within the main channel.
- The rate of bedload transport across the whole catchment is predicted to increase by up to 73% with climate change, and a 1:5 year flood with climate change would increase channel instability and bedload transfer rate to that of a current 1:10 years flood, and the same pattern is seen between a 1:30 year flood with climate change and a current 1:50 year flood, and 1:50 year flood and a currant 1:100 year flood.
- The DRN provides an easy-to-use interface, which can be used by scientists and river managers with a good knowledge of fluvial geomorphology, to investigate changes in channel stability, and the impact of different flood flows, and the impact of climate change on rivers; but with the proviso that the assumptions and simplifications made within the model are acknowledged.

Objective 4: to assess the importance of habitat structure on allowing aquatic species to avoid entrainment, with specific reference to the freshwater pearl mussel.

This objective was addressed in Chapter 5 of this thesis. Here the aim was to investigate what parameters were important in allowing the critically endangered freshwater pearl mussel to avoid entrainment under flood flows. This included looking at the different behavioural defence mechanisms of burial, sheltering and alignment; and physical characteristics such as weight, shell length and shell curvature. The main conclusions from this are:

- Sheltering was found to be the most effective defensive mechanism for allowing freshwater pearl mussels to avoid entrainment. This was because it protected the mussels from the high velocities associated with high flow events. In association with this, it was found that river habitat was the important factor in allowing mussels to prevent being entrained, with a boulder-bed being more effective than a mixed-bed or sand-bed – with mussel distribution being behind boulders.
- The results suggest that river habitats which contain large boulders provide the mussels with the best protection against flood flows. Thus it is suggested that conservation efforts should ensure that these habitat areas are protected, as they are likely to represent key areas for mussel recruitment and population growth, making them key to the survival of the species.

Objective 5: to examine the potential effect that changes in flood frequency and climate change could have on river ecology, specifically with reference to the critically endangered freshwater pearl mussel

This objective was addressed in Chapter 6 of this thesis. Here the aim was to investigate the ability of using the spatially developed Digital River Network (DRN) model (developed in Chapter 4) to assess the potential effect of changing flood frequency, and the predicted changes in future climate, on a benthic dweller – namely the freshwater pearl mussel. The freshwater pearl mussel was used as a case study due to its critically endangered status, and the known importance of bed stability in the mussel's ability to withstand flood flows. The main conclusions from this are:

- SEPA's DRN model provides a useful screening tool to aid in predicting mussel populations which are most vulnerable to different flood frequency magnitudes, and also the populations most at risk from future climate change. The ability to do this provides river managers, and those involved in the conservation of species (e.g. SNH), with a guide to where conservation should be prioritised. For example, by providing an insight into populations which will be important for mussel population recovery after high flow events.
- The DRN model suggested that mussel disturbance frequency would increase in the future with climate change for 3 of the 18 river reaches studied here that contained freshwater pearl mussels, by around 20 years, putting considerable strain on these mussel populations to recover to pre-disturbance numbers before the next high flow events occurs again.
- Despite the freshwater pearl mussel being used in this study, the DRN's ability to predict the frequency of habitat disturbance could be used to predict the effect of climate on other benthic species, or species such as Atlantic salmon, which have specific substrate habitat requirements for recruitment.

In Chapter 1 of this thesis a conceptual model (Figure 1.1) was drawn showing the links between each of the seven chapters in this thesis and where each chapter fits into the wider science of fluvial geomorphology and channel adjustment. Having reviewed the aims and the objectives of this study above, it is now time to review how the findings of this study have enhanced our knowledge on predicting channel adjustment, the potential impacts of climate change and future changes in channel stability. In Chapter 2 of this thesis the influence of one of the drivers for morphological change in river channels i.e.

discharge and more specifically the relationship between flood magnitude and frequency. Here, the results show that the frequency of geomorphologically relevant winter floods is likely to increase in the future under a climate change scenario leading to increased winter geomorphic activity and a higher risk of channel instability in the future, as the river will have higher stream powers and thus an enhanced ability to carry out geomorphic work. Having the ability to predict nationally or on a catchment scale where rivers will potentially become unstable due increased stream powers and increased rates of bedload transport is important for ensuring any legislative work carry-out on rivers for erosion or flood risk are sustainable. The two simple methods used in Chapters 3 and 4 to assess this showed that due to the complex nature of the fluvial system it is very hard to predict with a high level of certainty how different reaches will adjust to climate change. Chapter 3 looked firstly at how a change in discharge will increase the stream power of a reach and its ability to carry out geomorphic work as a means of predicting changes in channel stability. Chapter 4 then took this one step further by looking at how an increase in stream power would affect the rate of bedload transfer as a means of predicting changes in channel stability. Chapter 3 further demonstrates the difficulty in using thresholds to predict channel dynamics. Due to rivers having a continuum nature, there are often fuzzy boundaries between one process type another making it very hard to create thresholds between the 'distinct' types. Chapter 4 model predictions add to the current understanding of the difference between channel stability within tributaries and main trunk streams and around tributaries junctions (Rice et al., 2008; Reid et al., 2007). Tributaries were found to be more reactive to changes in discharge due to climate change compared to the main trunk streams. Chapters 5 and 6 address the link between channel morphology and the physical habitat of rivers. Chapter 5 showed the importance of changes in physical habitat and bed stability in protecting the freshwater pearl mussel by from high flow events. Chapter 6 highlighted the use of catchment scale models and the value of looking at physical habitat beyond the mesoscale when looking at how a species will response to climate change. Ultimately this thesis shows how a change in just one driver for morphological change, in this case discharge, can have significant knock on effects through-out the fluvial system.

7.3 MANAGEMENT SIGNIFICANCE OF THE RESEARCH

At present, river managers are attempting to work with rivers that are potentially undergoing significant changes in their hydrological and sediment regime due to climate change. With limited knowledge on how this may affect Scottish river channels, and where these changes will occur within a catchment, this is problematic. This thesis aids in providing an insight into how the predicted increase in the magnitude and frequency of flooding in Scotland due to climate change will affect channel stability, bedload transport capacity and aspects of benthic river ecology, on a catchment scale. The ability to do this is important for future river management and conservation projects, as it can help prioritise where investment in flood defence (e.g. set-back embankments, bank protection schemes, restoration and conservation) should be targeted. Furthermore, the ability to screen for areas of channel instability means that labour- and time-intensive field surveys can be better prioritised and undertaken in the most appropriate locations. By knowing that the number of geomorphologically-active flood flows is likely to increase means that river managers can implement strategies that are appropriate, and that they are better able to manage the potentially more dynamic nature of river systems in the future. Additionally, the ability to predict, admittedly with low levels of certainty, when different reaches within a catchment will become unstable is important when you consider that more and more infrastructure, such as roads, bridges and property, lies close to, and continues to be built close to, river banks. If there is an indication that this infrastructure is vulnerable to future high flow events, river managers would be better prepared to try and mitigate against these structures becoming damaged, with even the possible option of a withdrawal of agricultural activity from the floodplain, at an intense level at least. The ability to suggest at what flood frequency magnitude channel instability occurs, and how this could change with climate change, also has important implications for river ecology, especially those in which bed stability and structure is important. Currently, it has been suggested that climate change will impact these species, but less has been done to assess which sites are likely to be effected the most. The stream power bedload model used here offers managers the ability to locate, with some certainty, reaches whose physical habitat is important for certain species, and to make them aware of how these reaches will be affected by climate change; the results of which can be used to direct conservation efforts, and restoration projects, which would help lessen the impact of climate on the species affected.

7.4 UNCERTAINTY

When developing any model to understand the fluvial system or the environment in general there is always a level of uncertainty associated with the output. This is because it is hard to account for every process, internal and external force and parameter within the system being modelled (Haff, 1996). Other issues also arise from constraints on data quality and availability, effects of scaling and lack of knowledge or information on the topic (Sear and Darby, 2007). In this study, difficulties in gaining an accurate model input data at the catchment scale such channel depth will have increased the uncertainty of the model outputs. However, the level of uncertainty associated with poor data availability is likely to decrease in the future as data collection methods and quality of spatial data improves in the future (Bishop et al., 2012). Furthermore, assumptions must often be made due to a lack of knowledge or to reduce the complexity of the model to allow it to run and produce the results with limited computing power. In this study, assumptions and lack high quality data have increased the level of uncertainty associated with the outputs. These assumptions were made for two reasons i) lack of available data and ii) the desire to find a method to assess the sensitivity of different river catchments to changes in flood frequency magnitudes at the catchment and potentially national scale. When trying to predict changes in channel stability at the catchment or national scale there needs to be compromise between model complexity and the level of model error and thus model uncertainty (Fortmann-Roe, 2012). As Fortmann-Row (2012) explains the more parameters you add to a model the greater the model complexity is, but the variance (variability in model output) increases and your bias decreases (difference between predicted and observed results). Model error is therefore lowest at the point where variance and bias are at their lowest. Consequently, adding more parameters and increasing model complexity does not often result in reduced model error (Fortamnn-Roe, 2012). Assumptions therefore can be made to reduce the complexity of the model and as a result reduce model uncertainty. An example of this in this study is the bedload model used in Chapter 4. Predictions of the rate of bedload transport assume that sediment supply is constant. In supply-limited channels this will not be the case and the model will potentially over-predict the rate of bedload transport in these reaches. However, trying to predict sediment supply across the entire River Dee catchment would lead to more assumptions being made which would be hard to qualify and thus further increase uncertainty in the model output. The assumptions and uncertainty associated with simple tools to predict changes in channel stability, such as stream power and the bedload model used in this study, mean they are limited in their ability to be used as alone tool to make management decision within the fluvial system. Although, these simple tools can provide an indication of the location of potential risks in channel instability at coarser resolutions they lack the detail to provide an in-depth understanding into channel dynamics at high resolutions such as reach scale. Also, as demonstrated in this study, simple tools can provide a good indication of the extremes e.g. high deposition or high erosion but lack the ability to deal with complexity of the fluvial system and struggle to say with confidence what is happening in-between these two extremes. In essence, the uncertainty when using simple tools to predict channel stability and change is lowest at the extreme ends of the river continuum e.g. high erosion or high deposition and greatest in-between these extreme where there is a greater overlap in channel processes. As shown in this study when investigating stream power thresholds as a means of predicting different channel process types, this limits the ability of simple tools to be used when making decision about sediment dynamics at reach scale. However, if the assumptions within the analysis are understood and accounted for, simple tools, such as those used in this study to assess channel stability, can be useful to gain an understanding of the relevant difference between channel reaches and provide an indication of the sensitivity of a river to changes in flow at the catchment and national scale.

7.5 FUTURE WORK AND RECOMMENDATIONS

Future studies building on the work of this study would ideally first want to look at further model validation to ensure a higher level of accuracy when predicting channel instability and bedload transfer. This could be achieved through improvements in spatial data to gain more accurate slope, channel-width and channel-depth values; and more field survey work to aid in better definition of the parameters that determine channel typology and bedload grain-size diameter; and the use of bedload monitoring techniques to validate bedload transfer rates. Further model validation would improve model accuracy, leading to a better prediction of areas of channel instability and bedload transfer rates. Future work for the bedload transport model could involve the use of aerial photographs and old maps to look for erosional and depositional sites. This would help to further validate the outputs from the DRN bedload model. Building in the ability to link bedload transfer rates with bank stability would also be a valuable addition to the model, as it would allow reaches which act as sediment sources within the catchment to be identified. The ability to look at bank stability could also be useful in identifying areas where reaches are vertically or laterally unstable, which would be especially useful in areas where important infrastructure such as bridges and houses are located. This could include looking for bank erosion stream power thresholds for different bank materials such as clay, sand and glacial till. Once a critical stream power for bank erosion has been developed for different bank materials, this could be used to predict at what flood flow bank erosion occurs within a reach. The ability to be able to use the DRN to screen for areas of high bank erosion would be extremely useful for developers wishing to develop floodplain land. The development of a more scientifically rigorous method for identifying those river reaches, which could be described as ‘balanced’ or ‘threshold’ reaches, where the erosion and depositional processes within them are fairly balanced would further improve understanding of catchment processes. Additionally, the ability to highlight more accurately areas of extreme deposition within the catchment (e.g. possibly at tributary confluences) would be useful for assisting in flood management and flood mitigation. Focussing is needed on stream power as a tool for predicting channel change, investigating to see how the thresholds for deposition and erosion change between gravel-bed and alluvial channels, managed channels, unmanaged channels, upland channels and lowland channels; and potentially how this differs between modelled stream power and field survey stream power values. Doing this would allow the difference, if any, between river environments to be documented and known, so the right set of thresholds were used by river managers when implementing different river management practices, instead of assuming that the Brookes thresholds work as a 'one size fits all'. Finally, if the potential decrease in an aquatic species due to habitat disturbance, and species fatalities for different flood magnitudes, were known, along with population recovery time, the DRN could be used to provide an estimate of the effect of climate on species population numbers. This would give river managers a good grasp of the effect of climate on different species, and aid in prioritising those most in need of assistance to survive.

7.5 FINAL CONCLUDING REMARKS

Managers of the fluvial system have a difficult job, attempting to balance the needs of all those who rely on rivers and the ecosystem services they provide. These, for example, span from protecting the species that live within and around the river environment, to the human requirements of impoundment for power, and abstraction for drinking water and agriculture. In recent years this task has become even more difficult, as predicted changes in climate suggest, along with what has been proposed in this study, that the hydrological regimes of rivers within Scotland are changing, resulting in a greater frequency of higher-magnitude flood events. Models are a useful method to assess the sensitivity of changes to river channels in terms of their stability, morphology and ecology, to hydrological change. However, models will only ever be a simplification of reality to guide and influence decisions, due to the complexity of the river system, and will always be associated with a certain level of uncertainty. Although the level of uncertainty will diminish with advances in data collection and computing power, model uncertainty will never be completely removed. This is ultimately because it is extremely difficult to model every single interaction and feedback within the fluvial system. However, sometimes by simplifying the system, using sound geomorphological and hydrological principles, along with an acknowledgement of the assumptions made, and the sources of error and uncertainty within the model, river managers can still get a comprehensive idea of what is likely to happen within a river reach under difference climate and management scenarios. Furthermore, considering the scale at which you want to review channel stability is important; as, although simplifying the river system may not provide a very detailed analysis of what happens at the reach scale, it can provide a comprehensive review of what is happening at the catchment scale. Being able to see what is happening at the catchment scale allows river managers to take a more holistic approach. This approach helps ensure that sustainable solutions to flooding, protection of ecosystem services, and erosion are implemented. The ability to simplify the river system, and use spatial data, in order to look at channel stability and bedload transfer with climate change, and produce meaningful results, has been shown in this study. For example, although the use of stream power on a reach scale does not always portray the most accurate picture of channel change and stability, it does provide a sufficient review at a national scale of how vulnerable Scottish river channels are to change. Likewise, although using DRN to predict channel stability and changes in bedload transport would benefit from improved data input and validation, it still produces a meaningful result on a how a catchment is functioning, and how this will change with climate change; which has been proven to accurately predict channel instability in the River Dee. Looking forward to, in time, having simple tools such as stream power and the DRN to guide management decision, despite the uncertainty associated with these methods, will provide river managers with a good starting to point to know where potential problem may arise, and the ability to gain an idea of how the catchment is functioning to ensure a sustainable solution.

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